Radio Jets as Driving Mechanism of Fast Outflows: The HI View

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Radio jets as driving mechanism of fast outflows: the HI view

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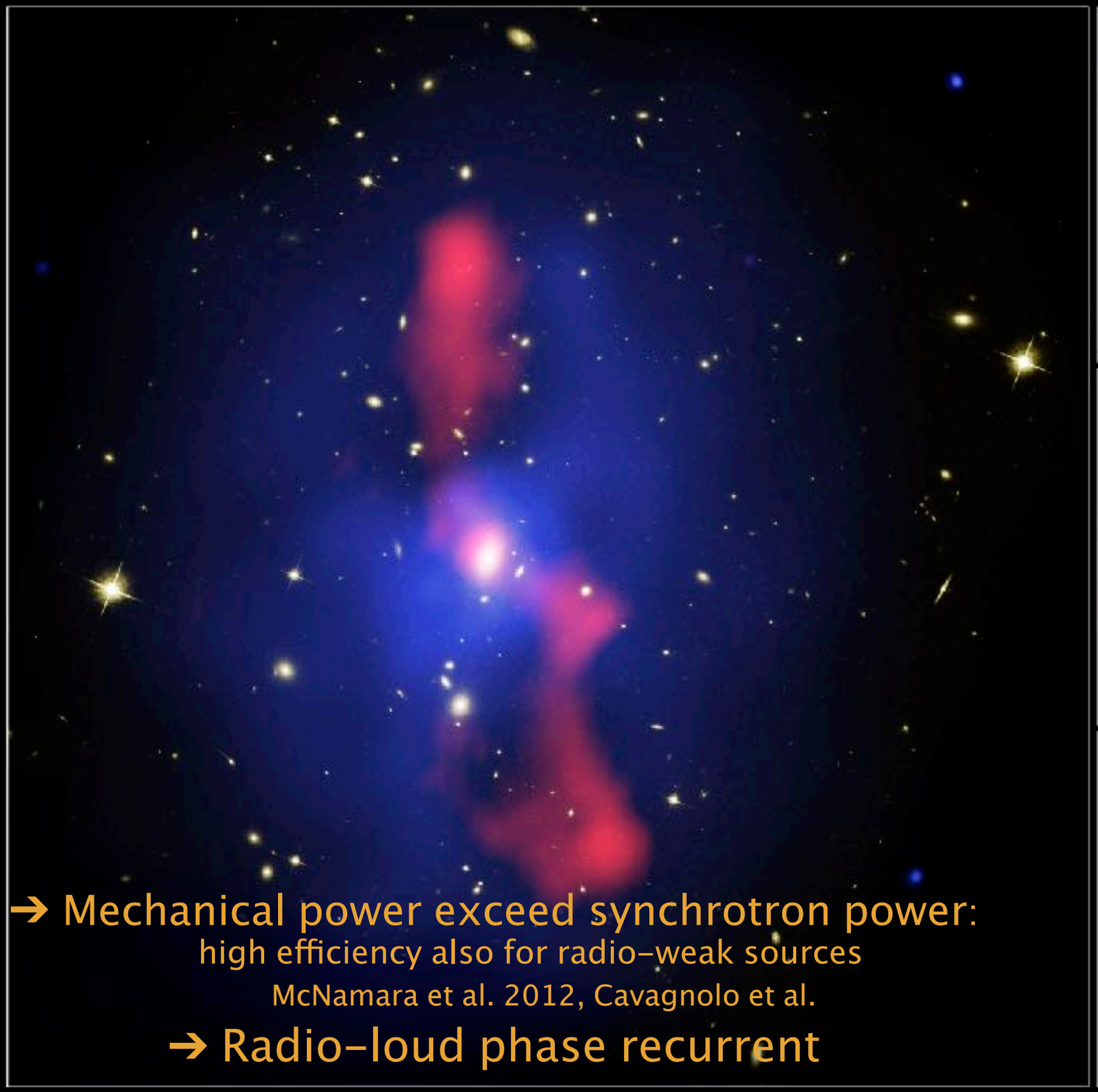
ASTRON and Kapteyn Institute

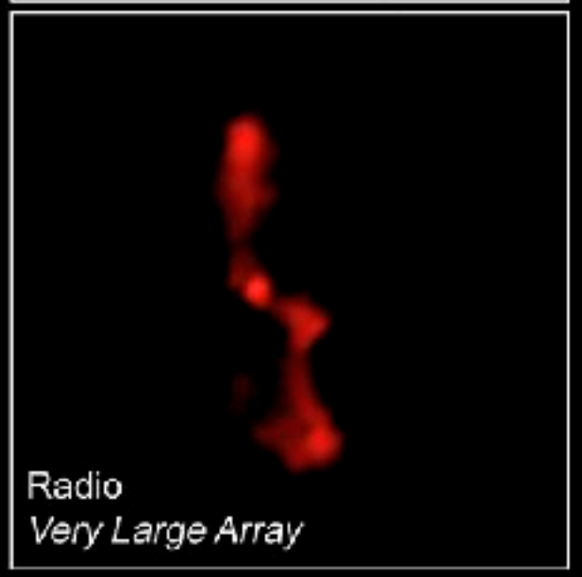
Galaxy Cluster MS 0735.6+7421

CXO ▪ HST ▪ VLA



X-ray
Chandra X-Ray Observatory

Visible
Hubble Space Telescope



Radio
Very Large Array

➔ Mechanical power exceed synchrotron power:
high efficiency also for radio-weak sources
McNamara et al. 2012, Cavagnolo et al.

➔ Radio-loud phase recurrent

NASA, ESA, CXC/NRAO/STScI, B. McNamara (University of Waterloo and Ohio University)

STScI-PRC06-51

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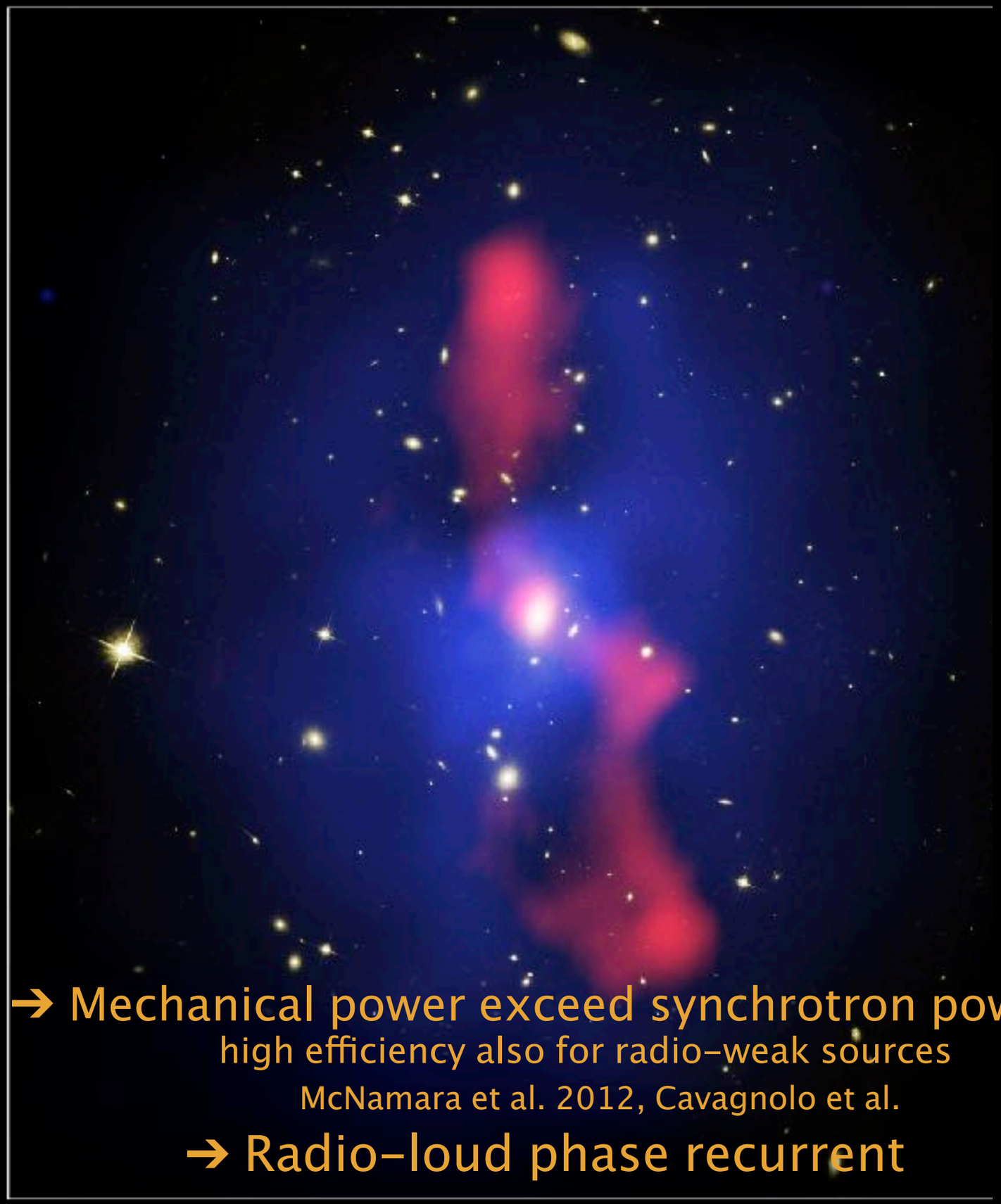

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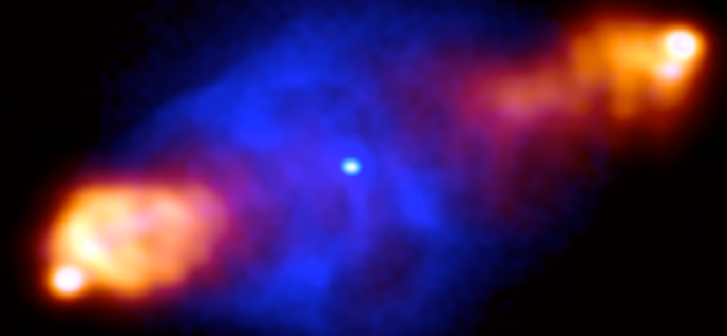
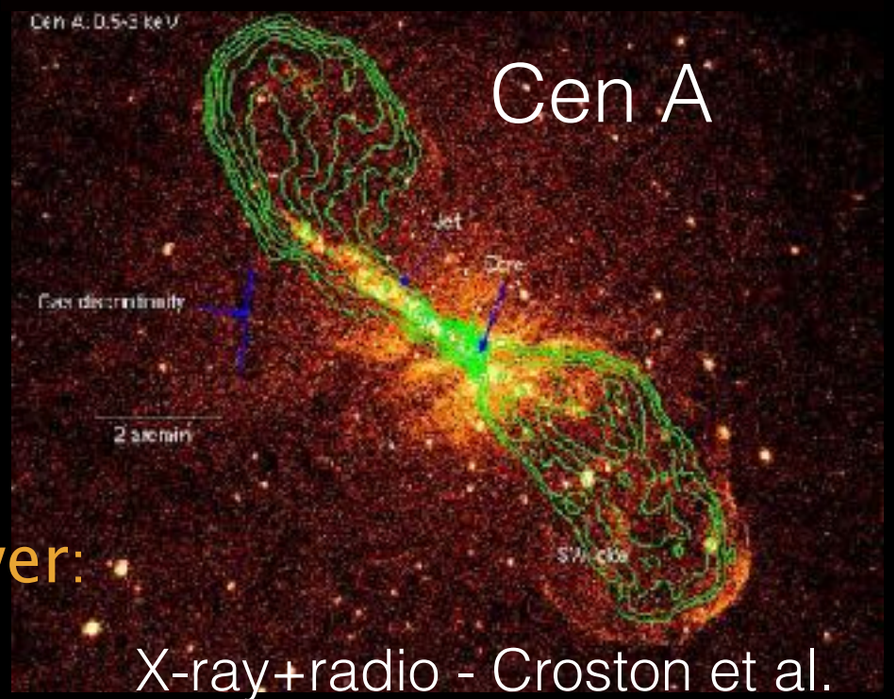
Cygnus A



LOFAR+Chandra

Wise et al., McKean et al.



Cen A

X-ray+radio - Croston et al.

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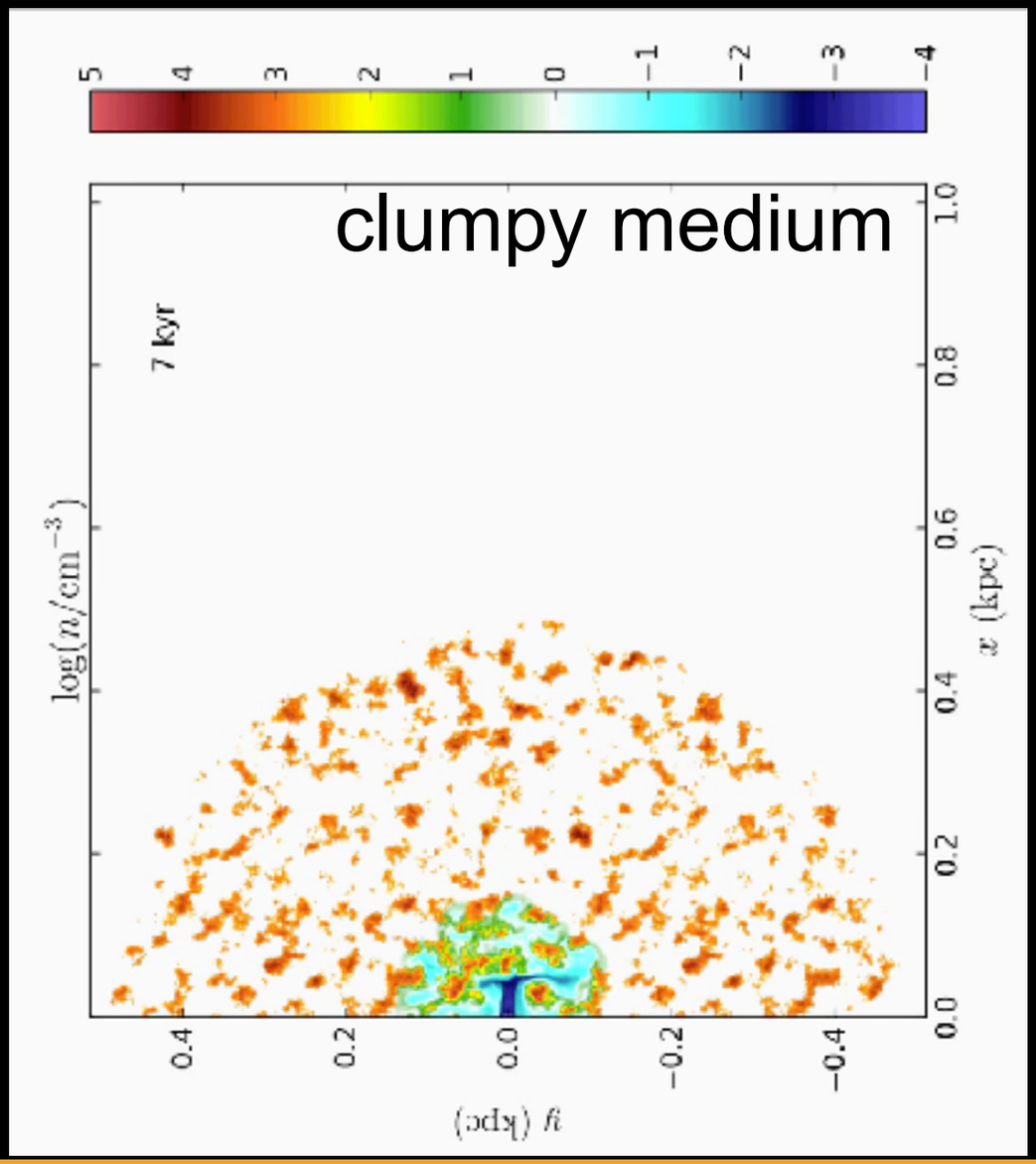
Impact of radio jets as predicted by numerical simulations: key parameter the clumpiness of the medium



Numerical simulation of a newly created radio jet

Wagner & Bicknell 2011, 2012

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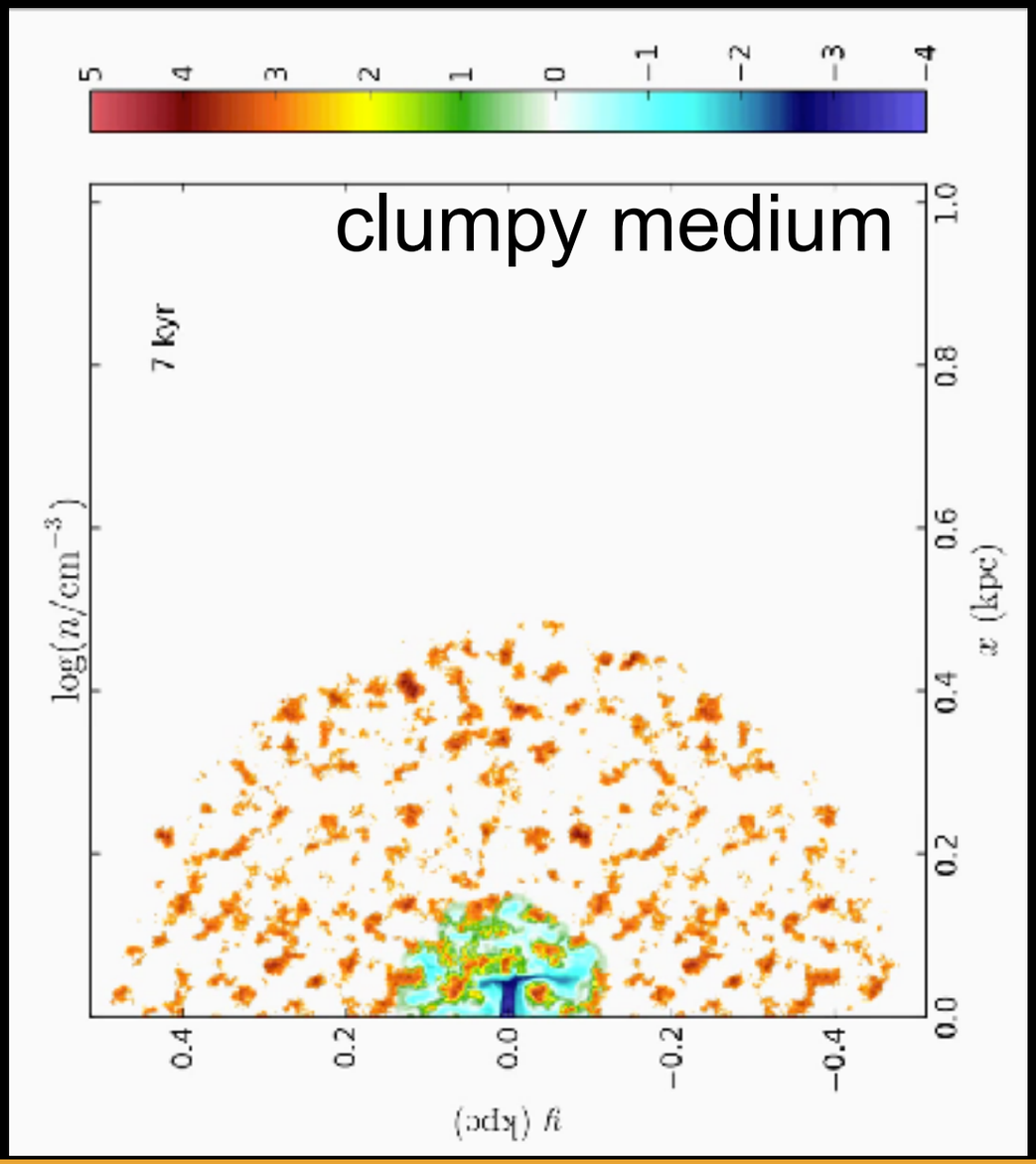

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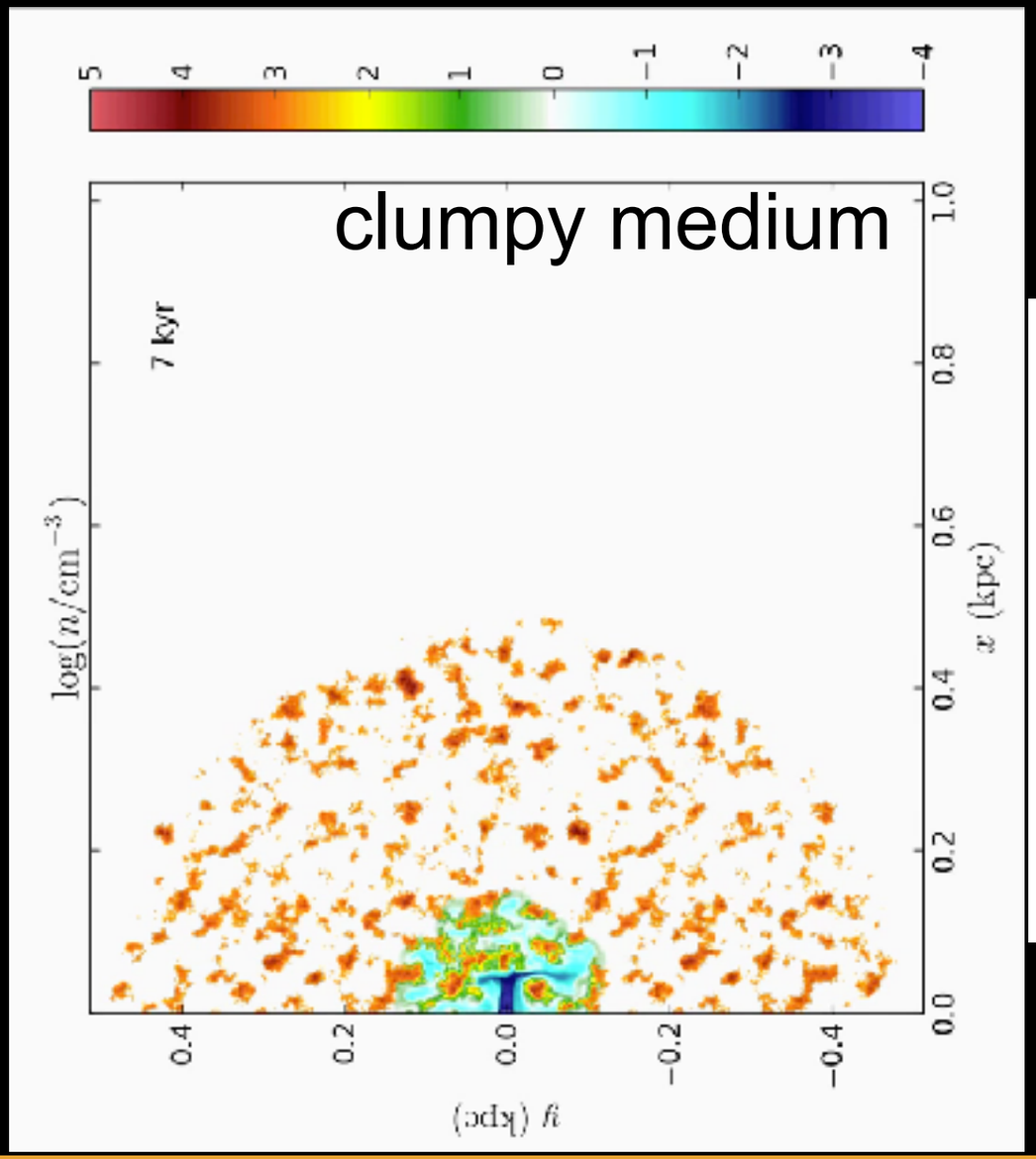
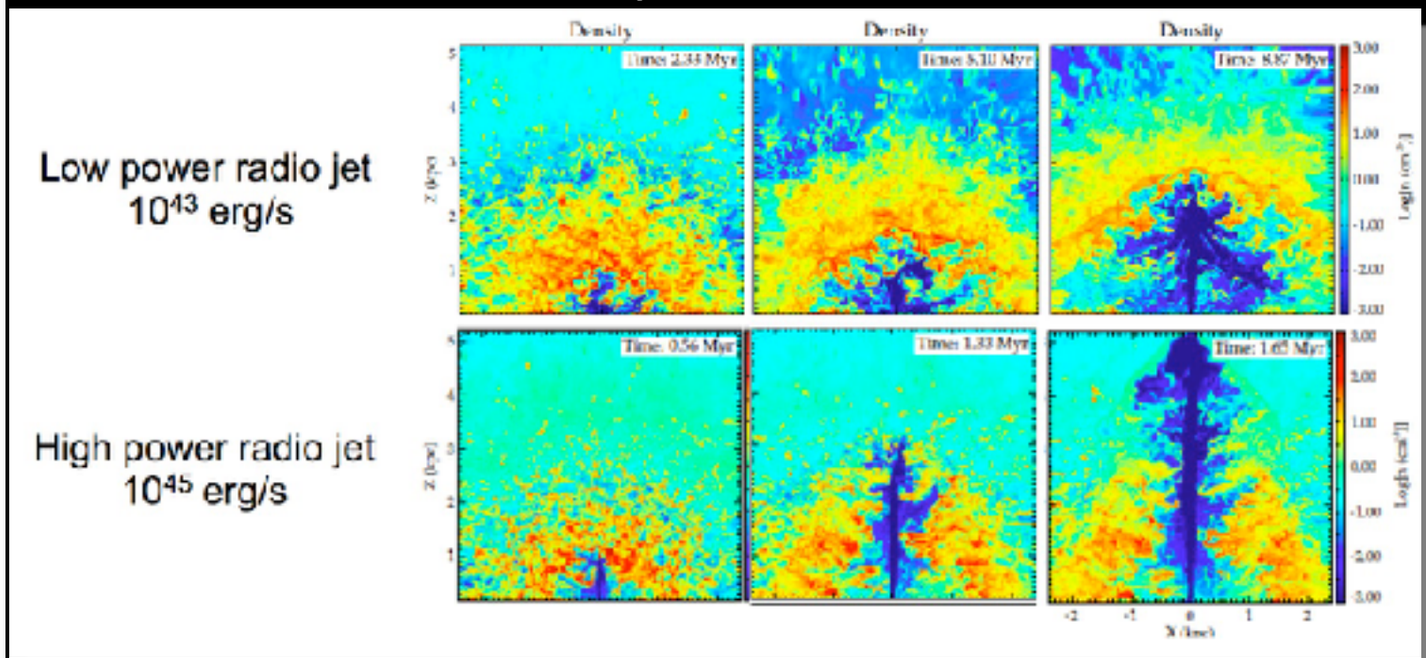


Trends with radio power
(from Mukherjee, Bicknell et al. 2016)



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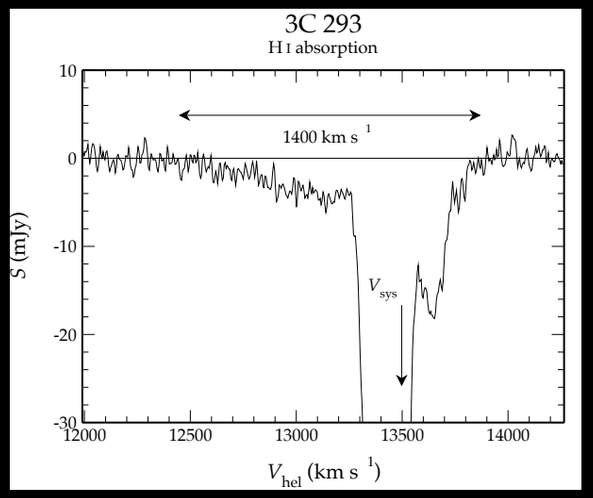
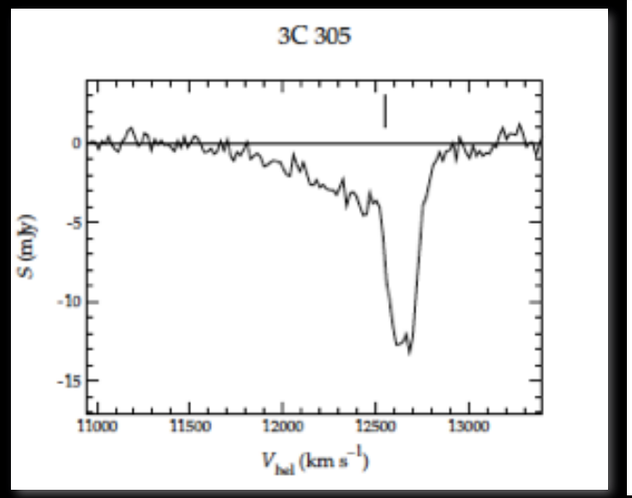
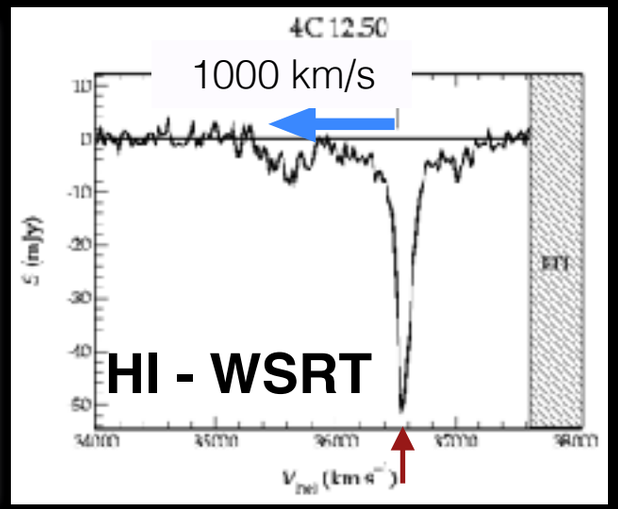
Importance of the cold gas…

Relevance for feedback:

discover of HI and molecular outflows….







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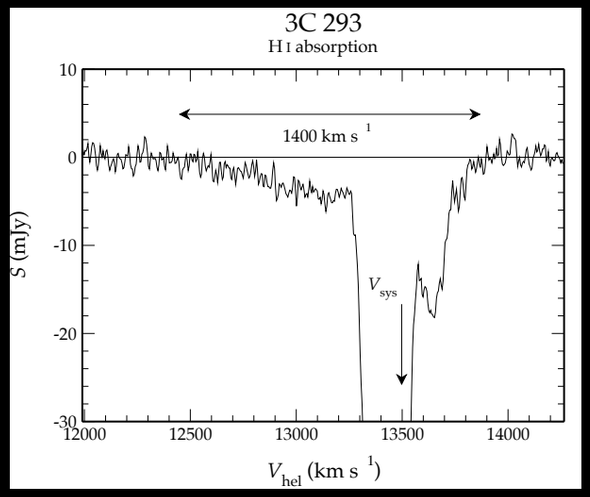

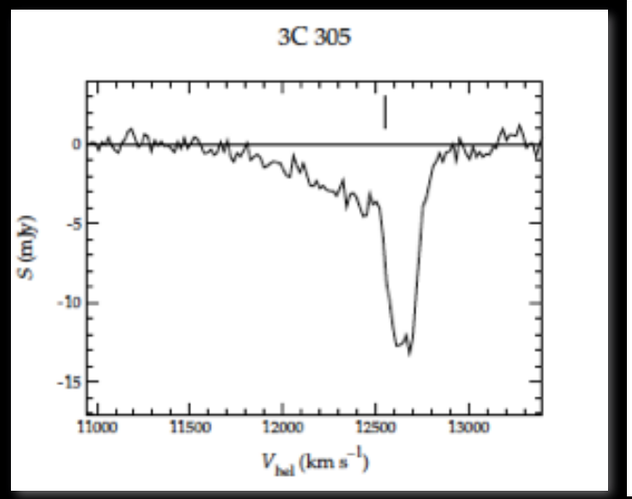

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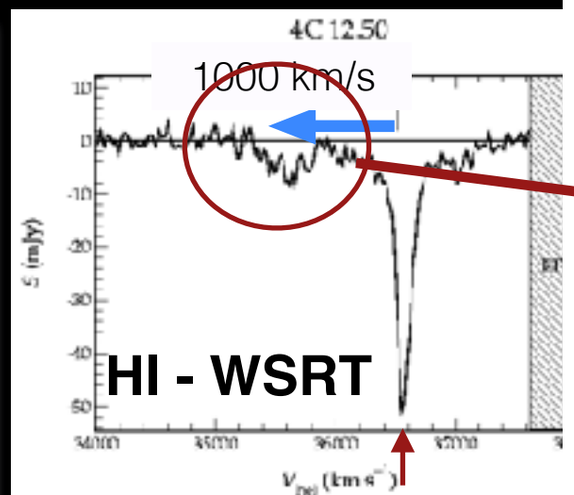

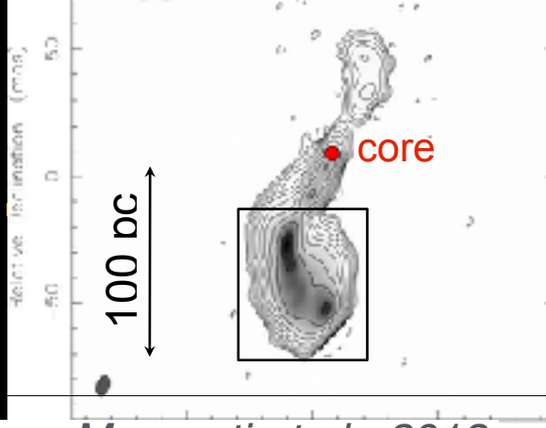

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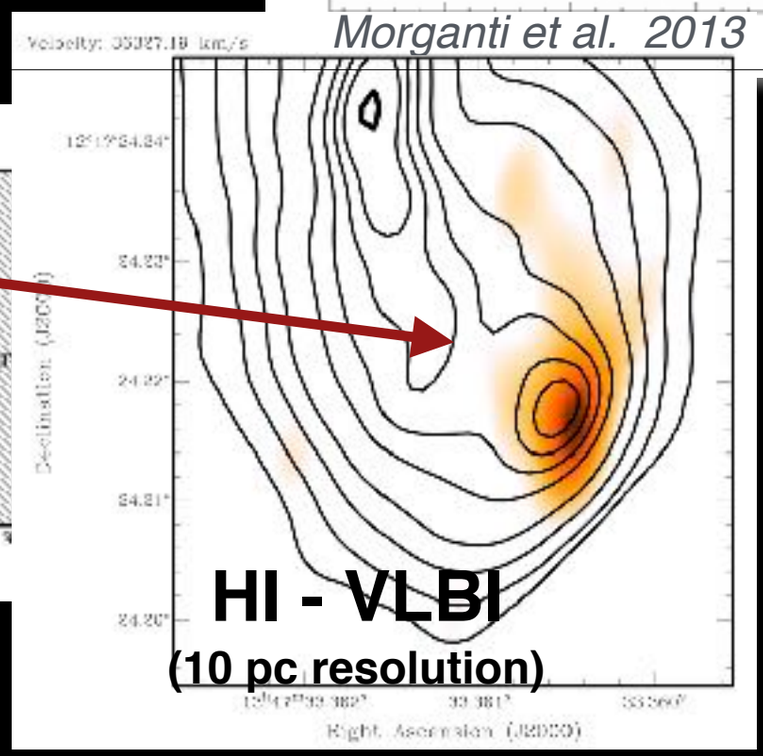

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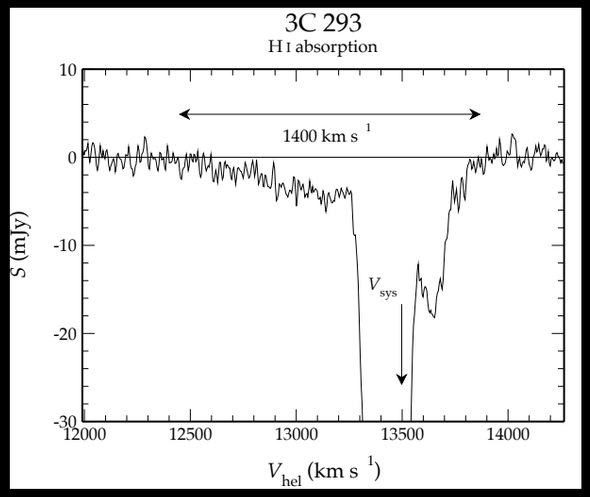

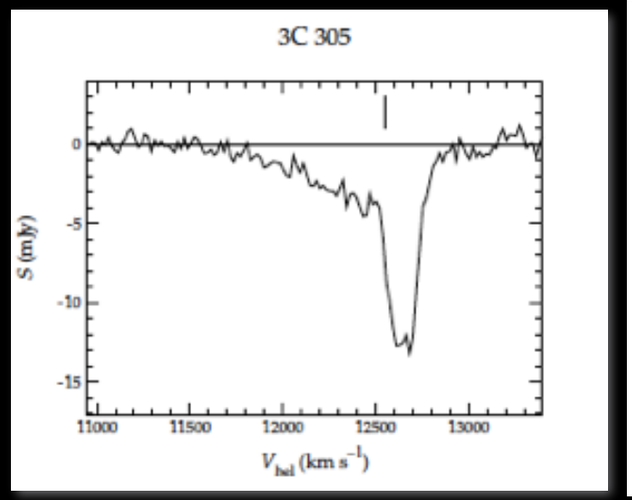

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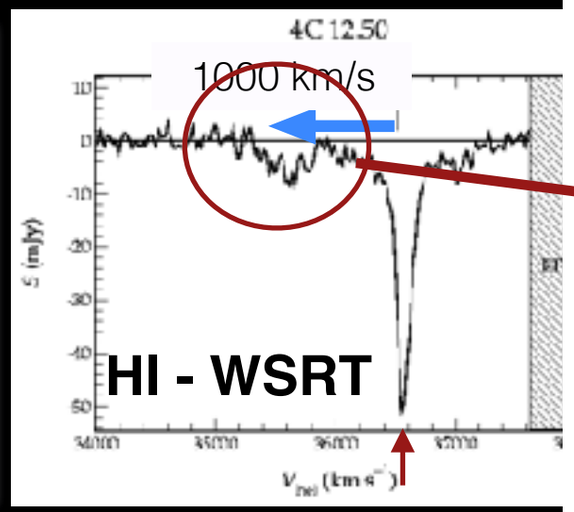

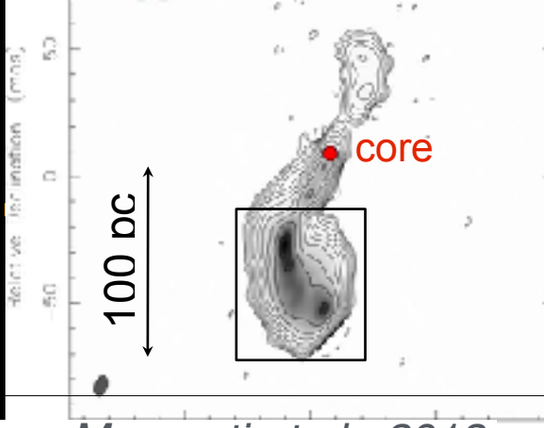

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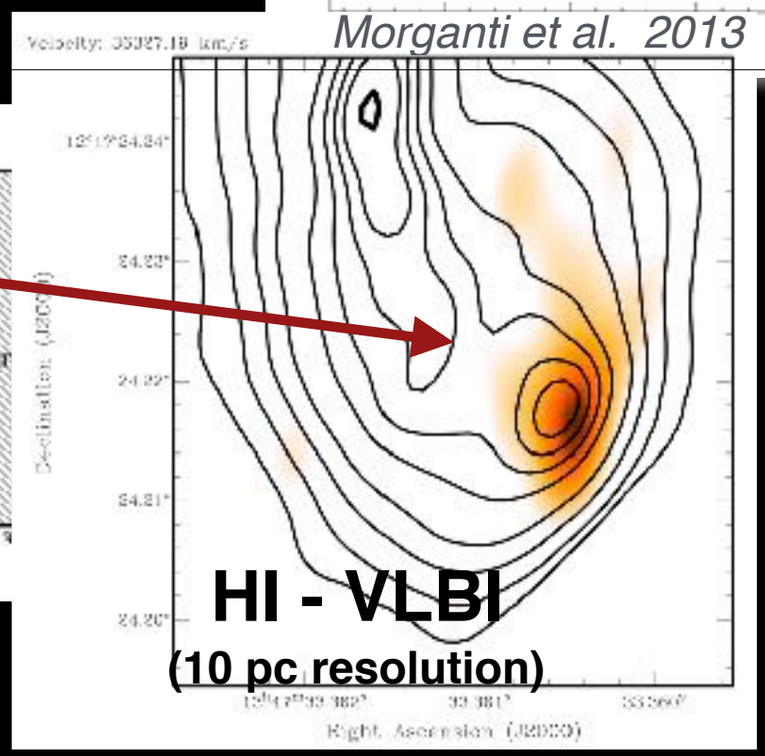
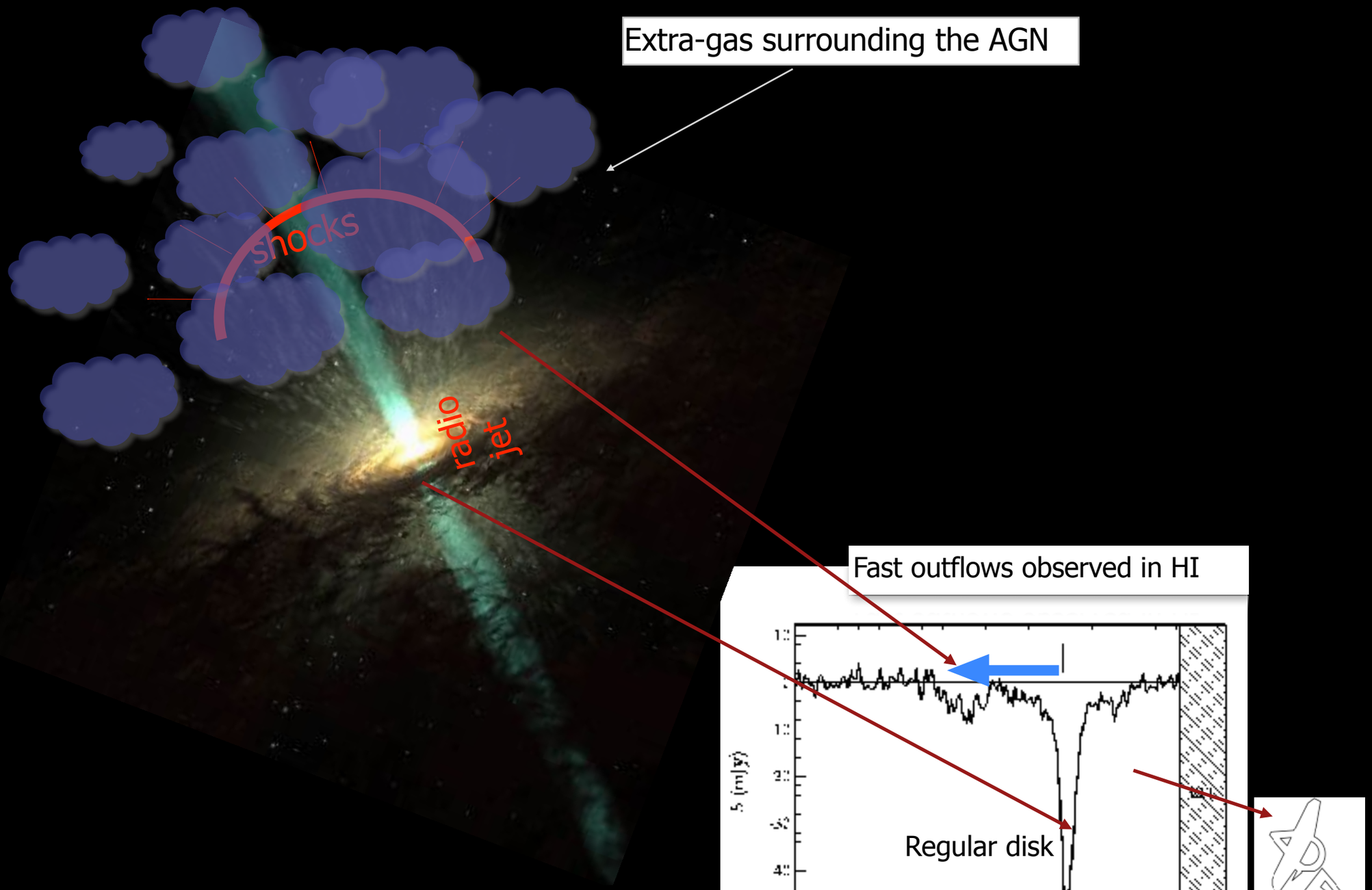


Using 21 cm - HI to trace whether radio jets have an impact on the kpc-scale ISM

Taking advantage of new technical capabilities of radio telescopes
and preparation for *upcoming new (blind) large surveys with SKA precursors*

Tracing outflows using associated HI absorption



Tracer of the gas in the inner parts of the galaxy close to AGN

- *Tracer of circumnuclear disks*
- *Infalling gas ➔ feeding*
- *Outflowing gas ➔ feedback*

Shallow HI absorption survey with the “old” WSRT

Recent survey to have a first uniform (but shallow) census

➜ 248 sources observed with the WSRT

[Gereb et al. 2014,2015, Maccagni et al. 2017]

Radio sources from FIRST and SDSS

$S_{1.4GHz}$ > 30mJy identified with z<0.26:
importance of ancillary data!

Red-sequence galaxies but variety WISE colours

66 Detections
27 % detection rate

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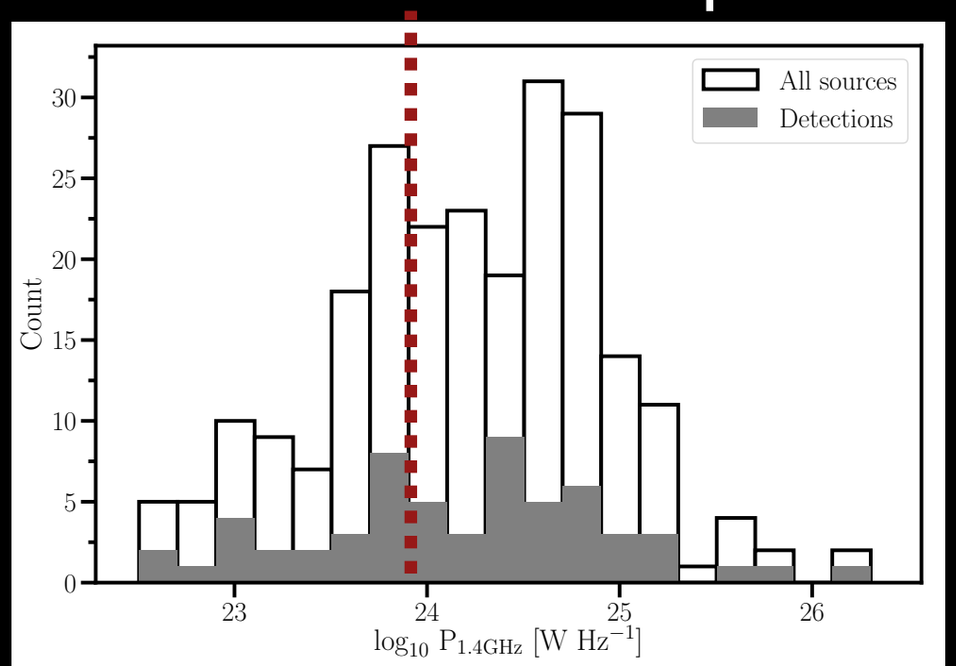
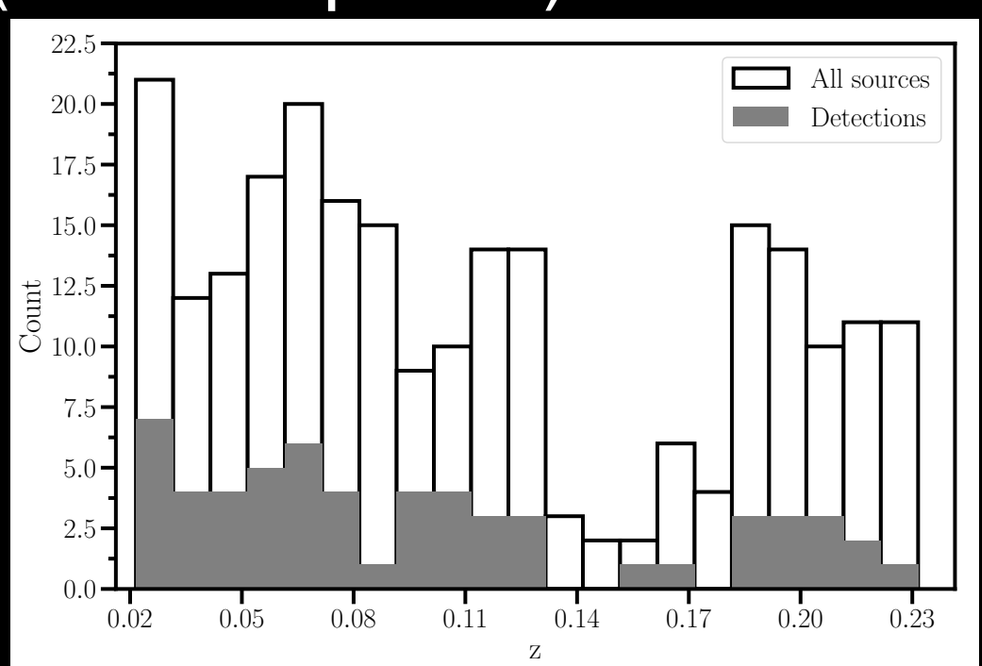
HI detections at all radio powers (also low power) and all redshifts

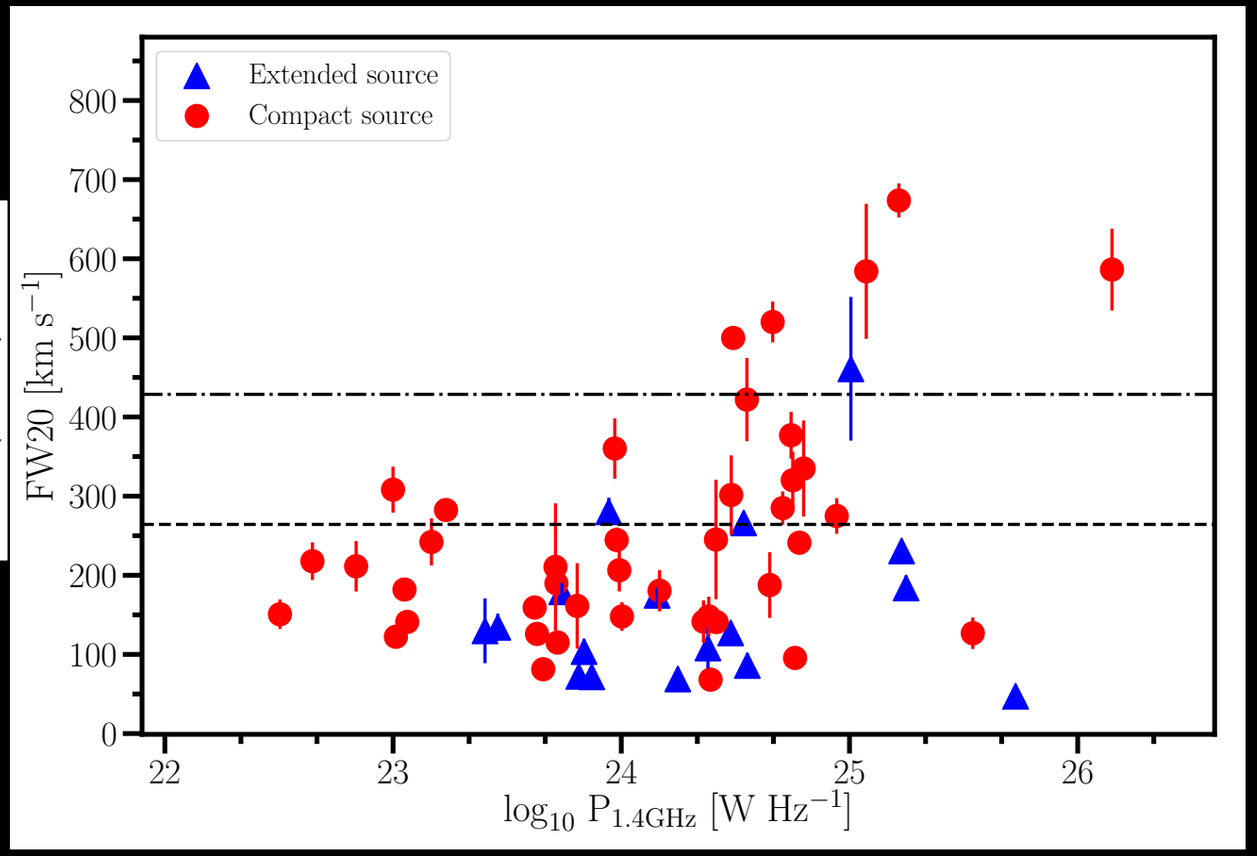


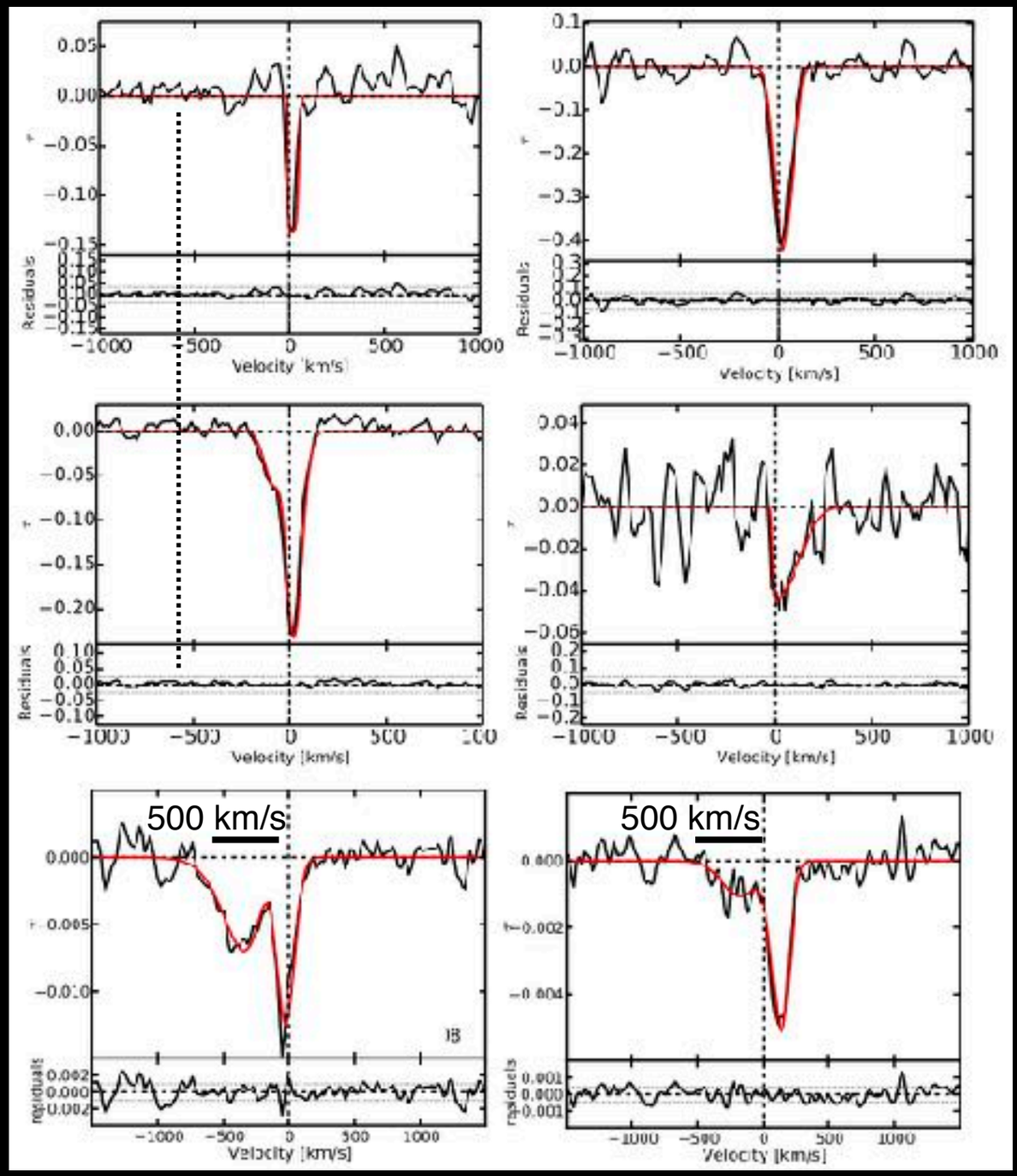


Variety of HI profiles

➔ the distribution and kinematics of the absorbing HI gas appear to depend on radio power, the properties of the radio continuum emission, and the dust content/farIR of the sources.

Powerful radio sources (or strongly interacting systems) have very broad HI absorption
Dust-poor have narrow HI profiles





70 km/s < FWHM < 640 km/s

5% of the sources show HI outflows
(15% of the detections) ➔ lower limits

[Gereb et al. 2014,2015, Maccagni et al. 2017 https://arxiv.org/abs/1705.00492*]*

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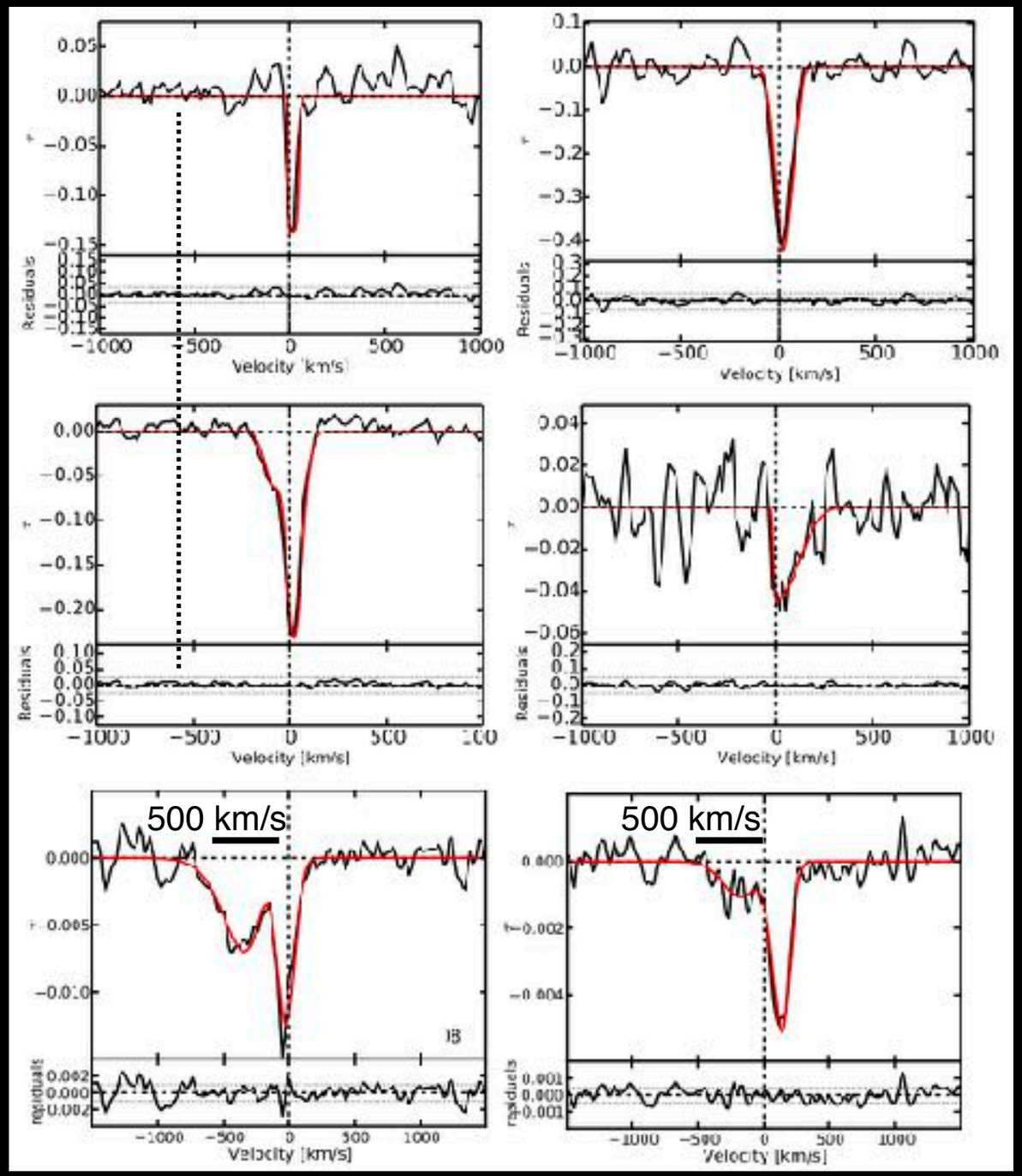

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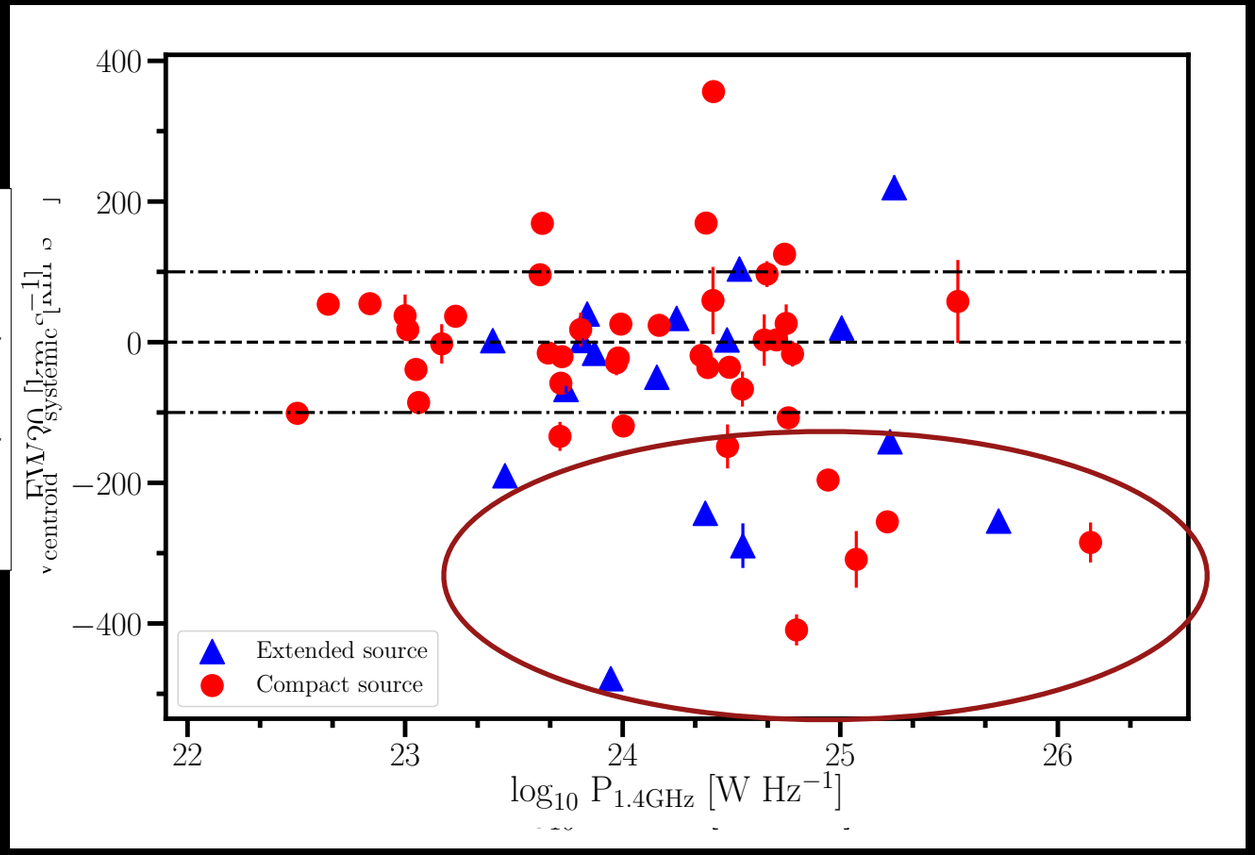

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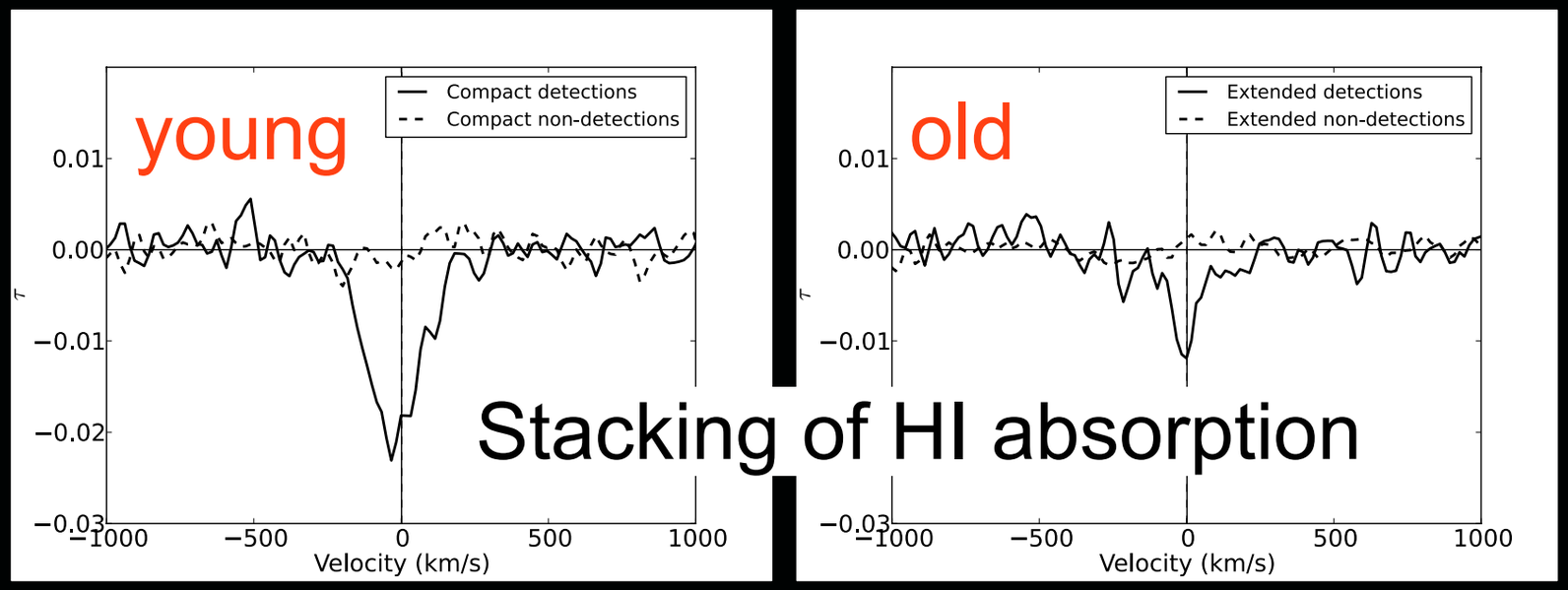
An evolutionary sequence?



Stacking of HI absorption

Difference in the HI properties of young/compact and extended

but in both cases group of objects undetected

Gereb, Maccagni, RM et al. 2015 A&A

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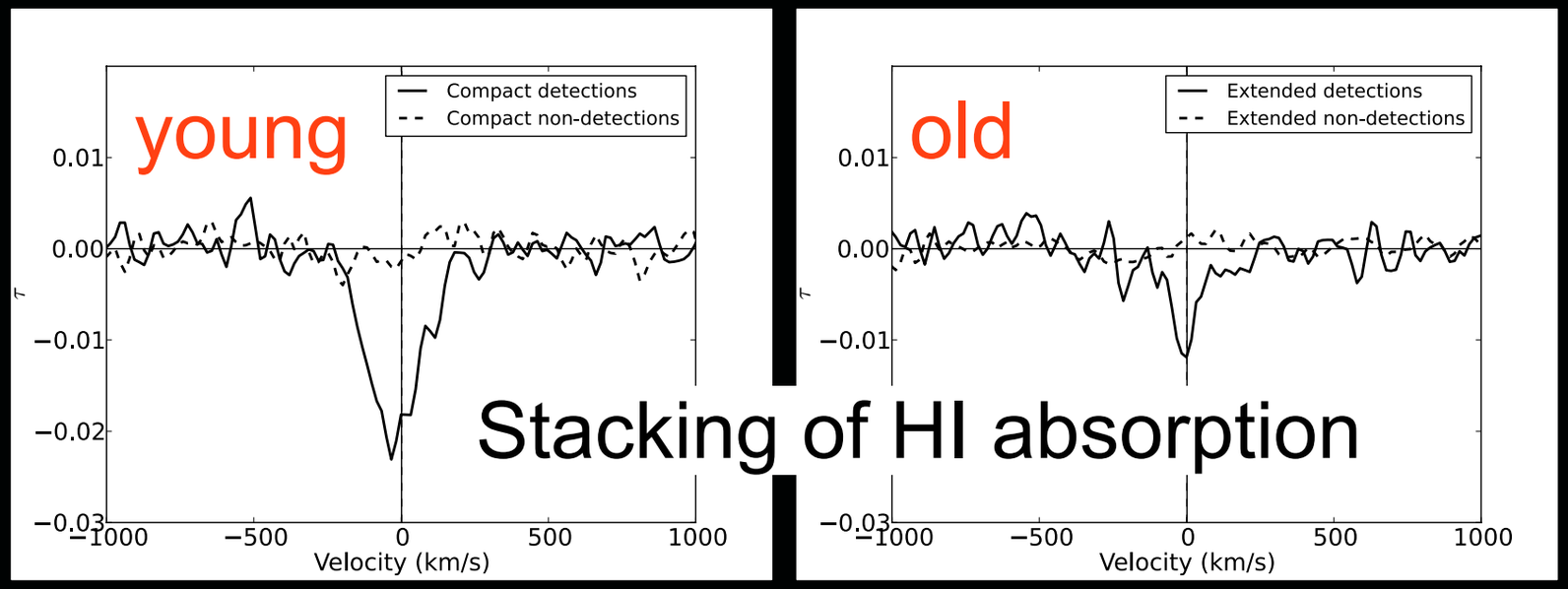

Stacking of HI absorption

Difference in the HI properties of young/compact and extended

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A strong connection between presence and characteristics of HI and the evolutionary stage of the radio sources

Young (or restarted) radio sources have:
➔ higher detection rate of HI
➔ higher optical depth/column density, FWHM
➔ gas more unsettled: most of the out➔ jets interacting clearing their way

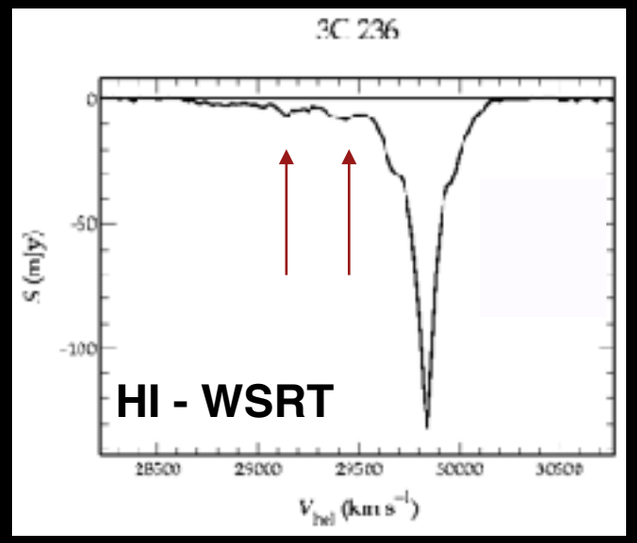
➔ transient phenomenon?

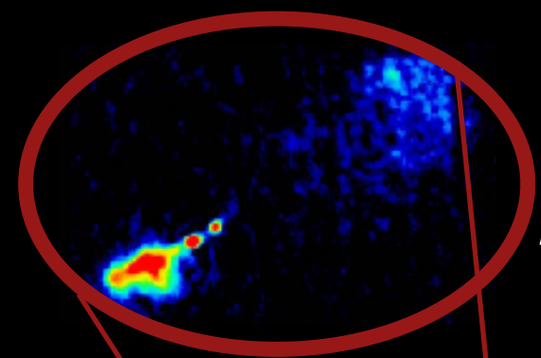
Gereb, Maccagni, RM et al. 2015 A&A

The importance of follow up at high resolution: 3C236

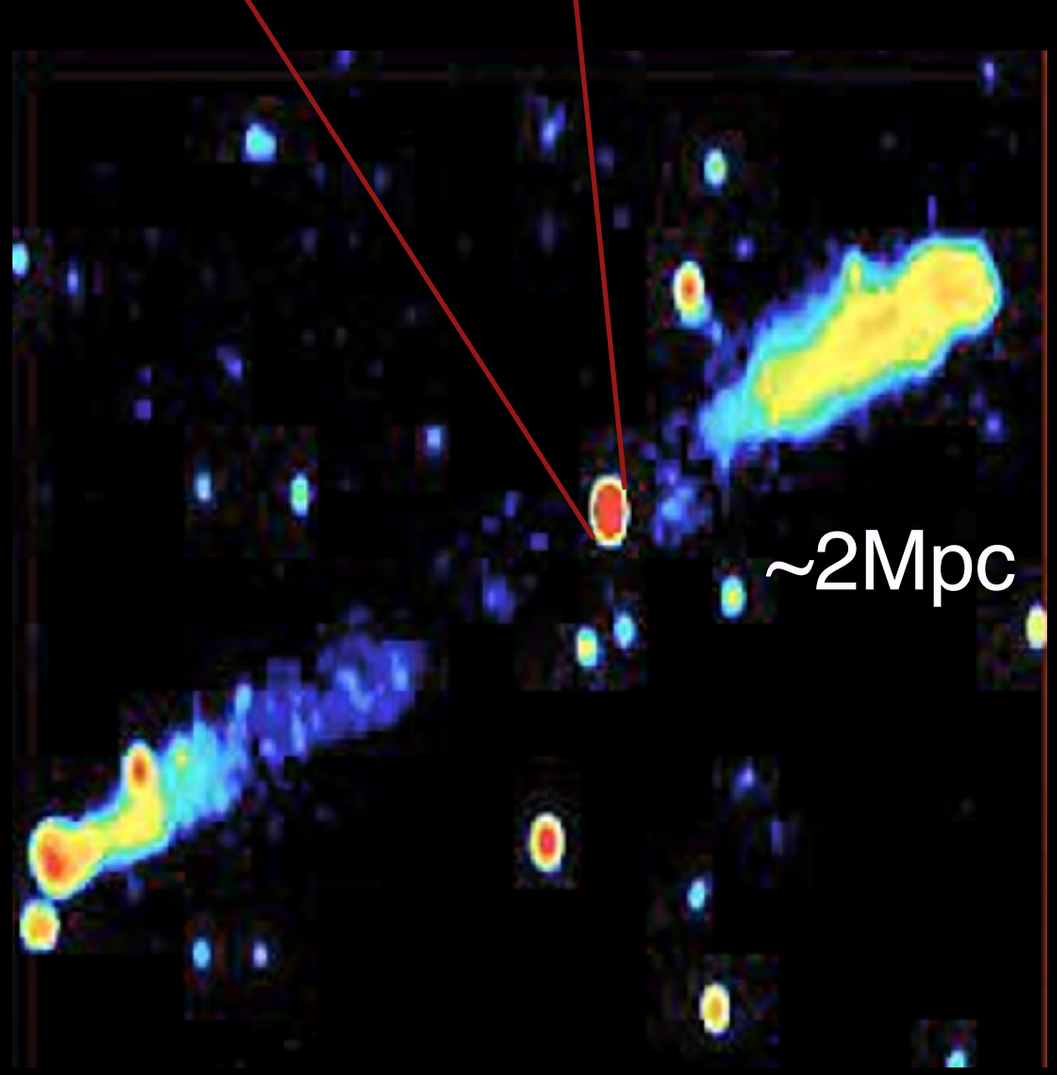
20 pc resolution - VLBI observations

Schulz et al. in prep.





~2kpc



~2Mpc

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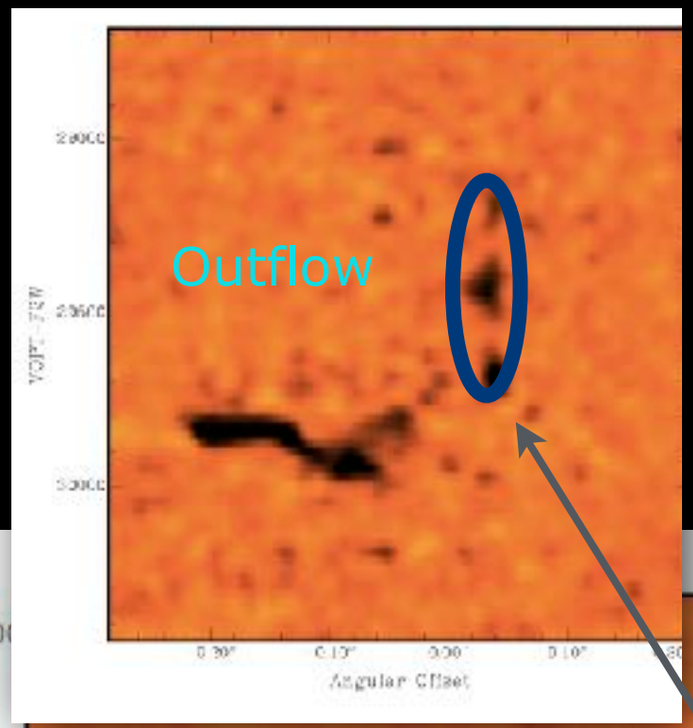
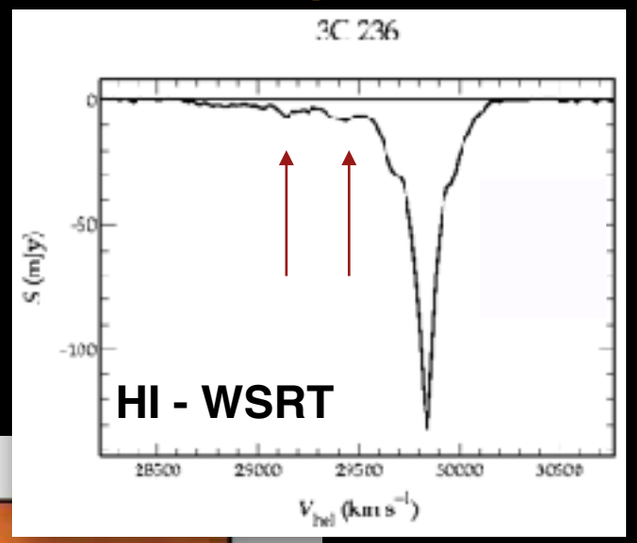
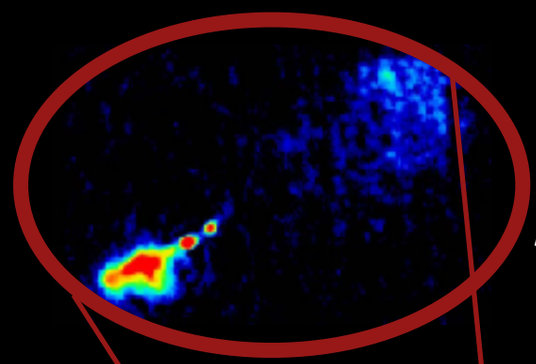


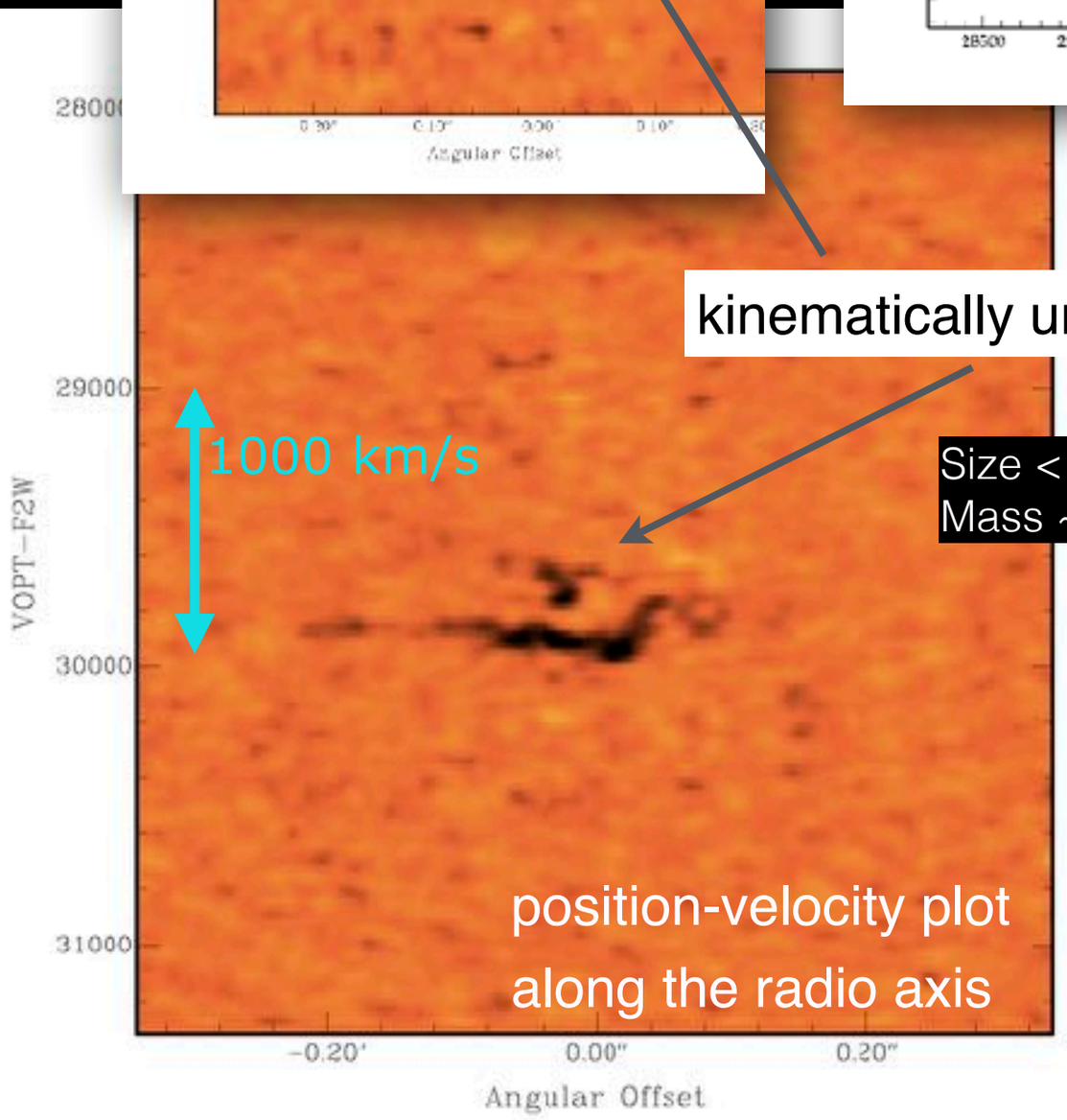


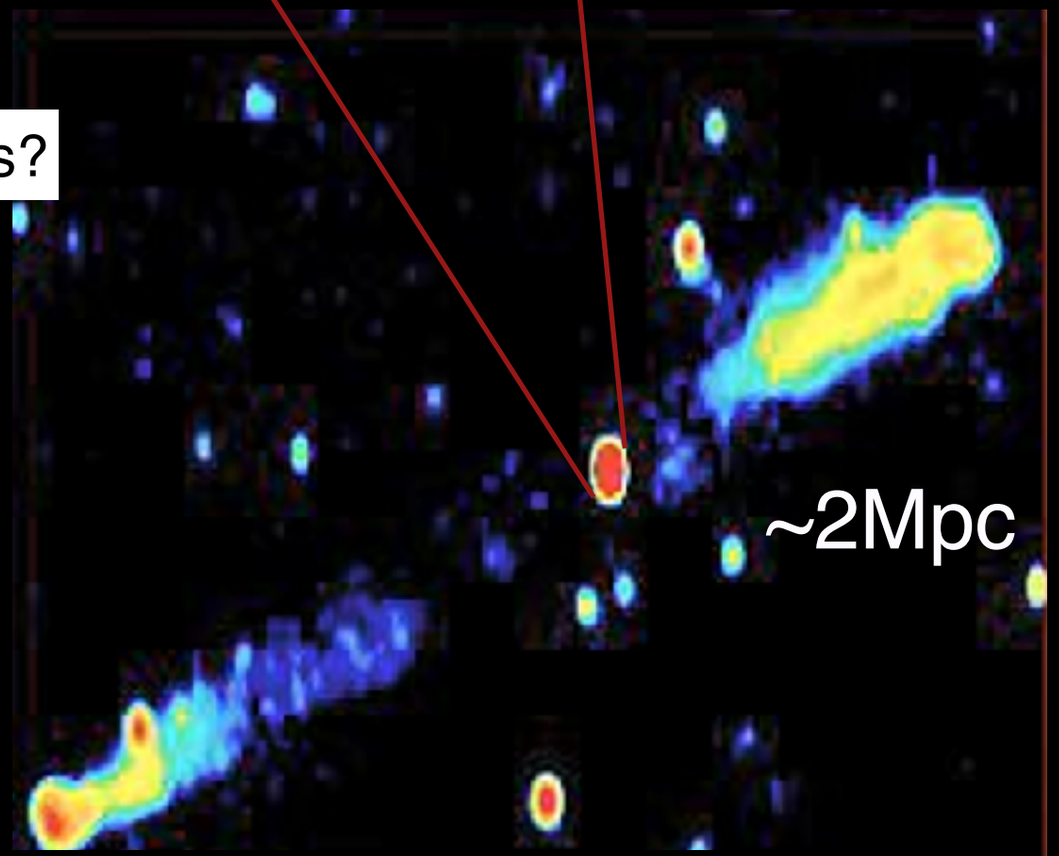


~2kpc

kinematically unsettled clouds?

Size < 40 pc
Mass ~ few x 10^4 Msun





~2Mpc

Signatures of clumpy medium
(together with a diffuse component?)

Parameters of HI outflows

HI outflows observed in the inner part (~ few hundred pc to kpc) of radio galaxies
(limited by the extension of the continuum)
Velocities between a few hundred and ~1300 km/s

- Mass in the HI outflows from a few x10^6 to 10^7 $M_\odot$
- Mass outflow rate → from a few to ~ 30 M⊙/yr
- HI outflow kinetic power ~ 10^{42} erg s^{-1}
- Eddington luminosity $\dot{E}_{kin}/L_{edd}$ = ~10^{-3} - 10^{-4}

→ mass outflow rate and efficiency smaller than required by feedback in simulations

- Clumpy medium: mass of the clouds ~10^4 $M_\odot$

→ Gas efficiently cooling after the interaction: cold molecular final product, warm molecular and HI intermediate (and less massive) phases

See also poster Richings

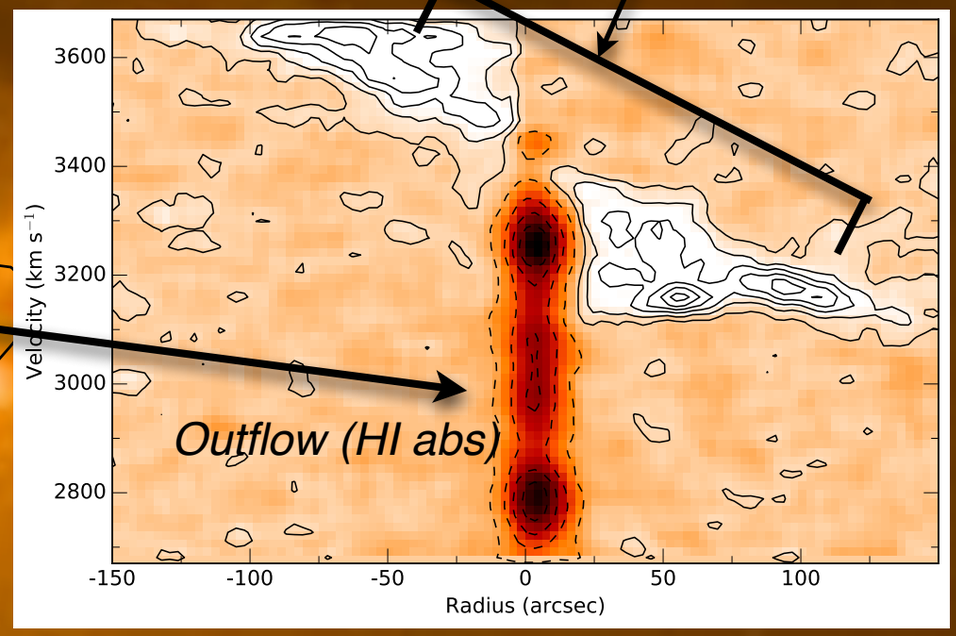
Multi-phase nature of AGN-driven outflows:

synergy with molecular gas

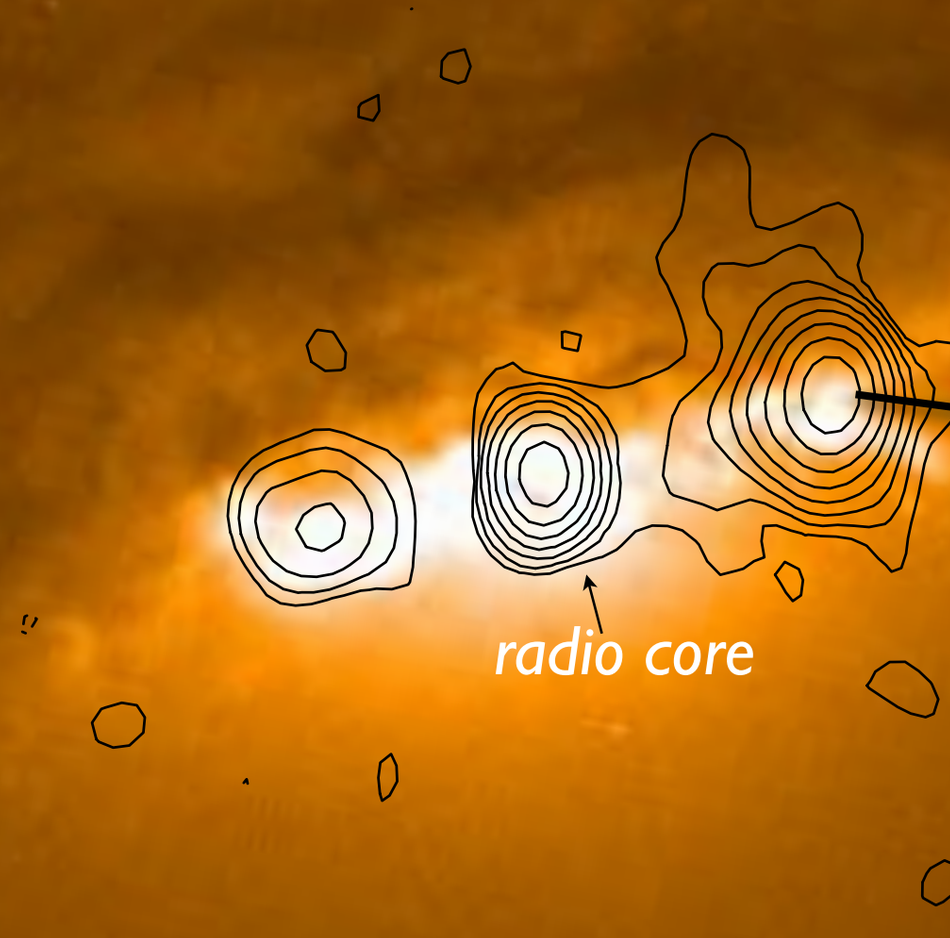
Effect of radio jets
The case of IC5063

Seyfert 2 (similar to NGC1068) strong optical AGN and radio power 3×10^{23} W/Hz @ 1.4GHz

Galaxy rotation (HI emission)



Morganti et al. 1998



~ 0.5 kpc

Known multi-phase gas outflow (HI, ionized gas and warm molecular)

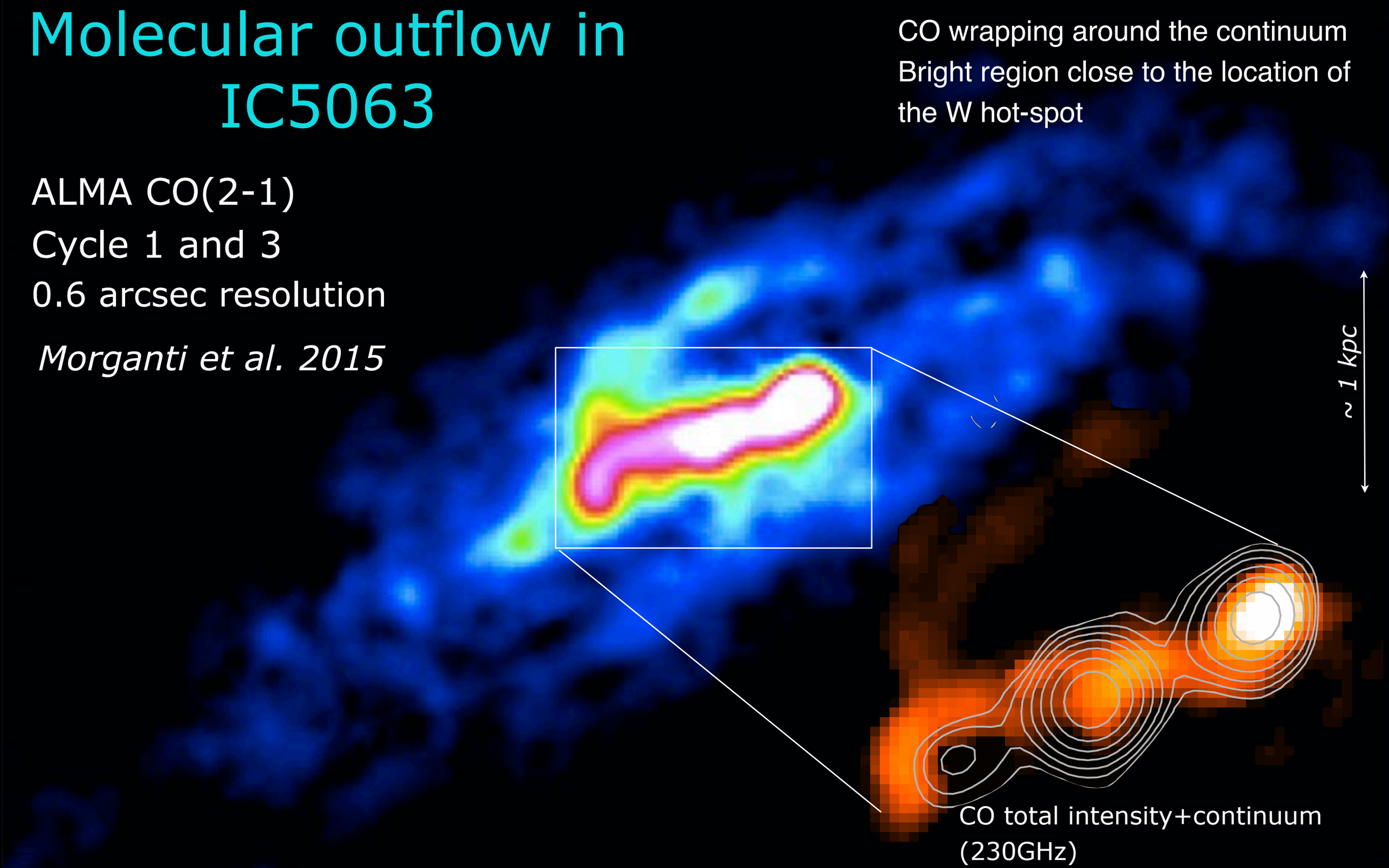
Tadhunter, Morganti et al. 2014 Nature

Molecular outflow in IC5063

ALMA CO(2-1)
Cycle 1 and 3
0.6 arcsec resolution

Morganti et al. 2015

CO wrapping around the continuum
Bright region close to the location of the W hot-spot



CO total intensity+continuum
(230GHz)

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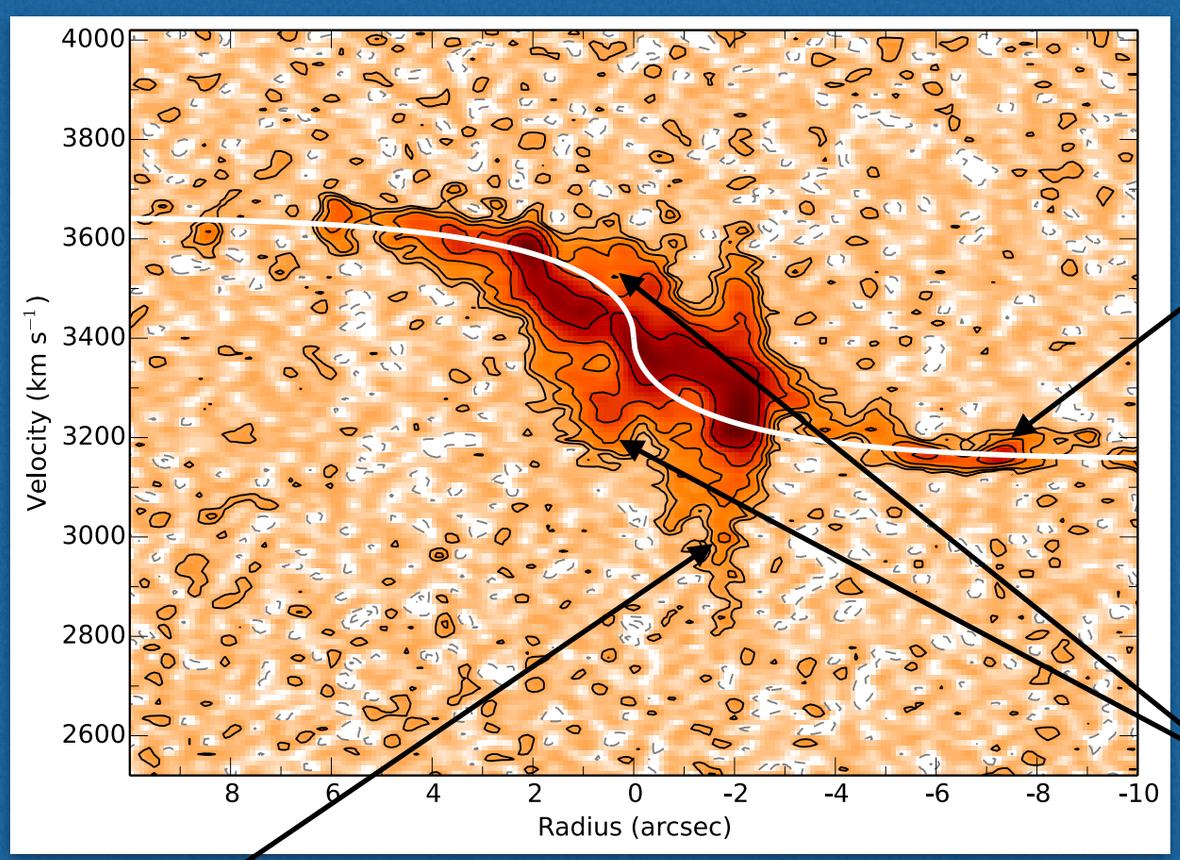
~ 1 kpc

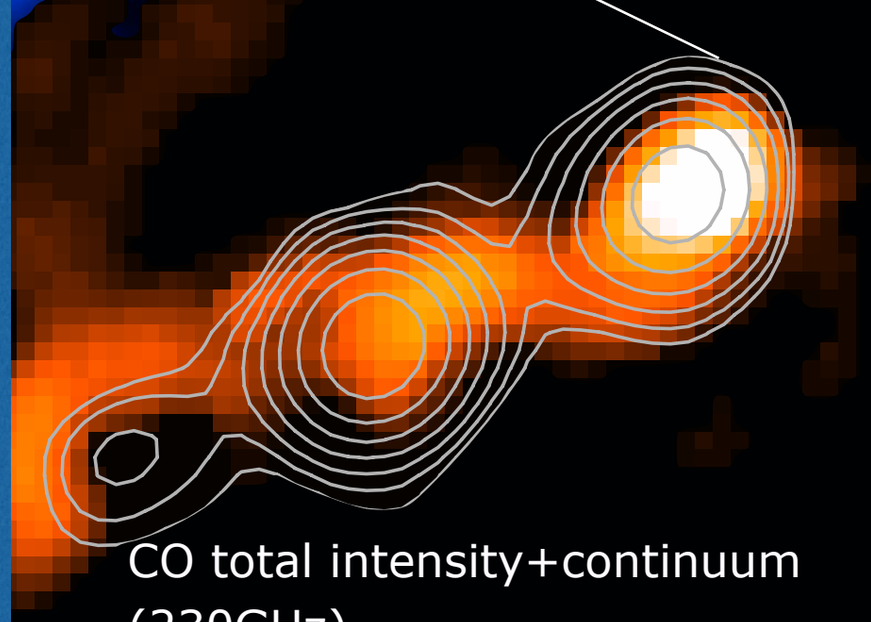


Regular disk

Outflow (cocoon)

Extreme outflow
at hot spots

pv diagram of CO(2-1)



CO total intensity+continuum
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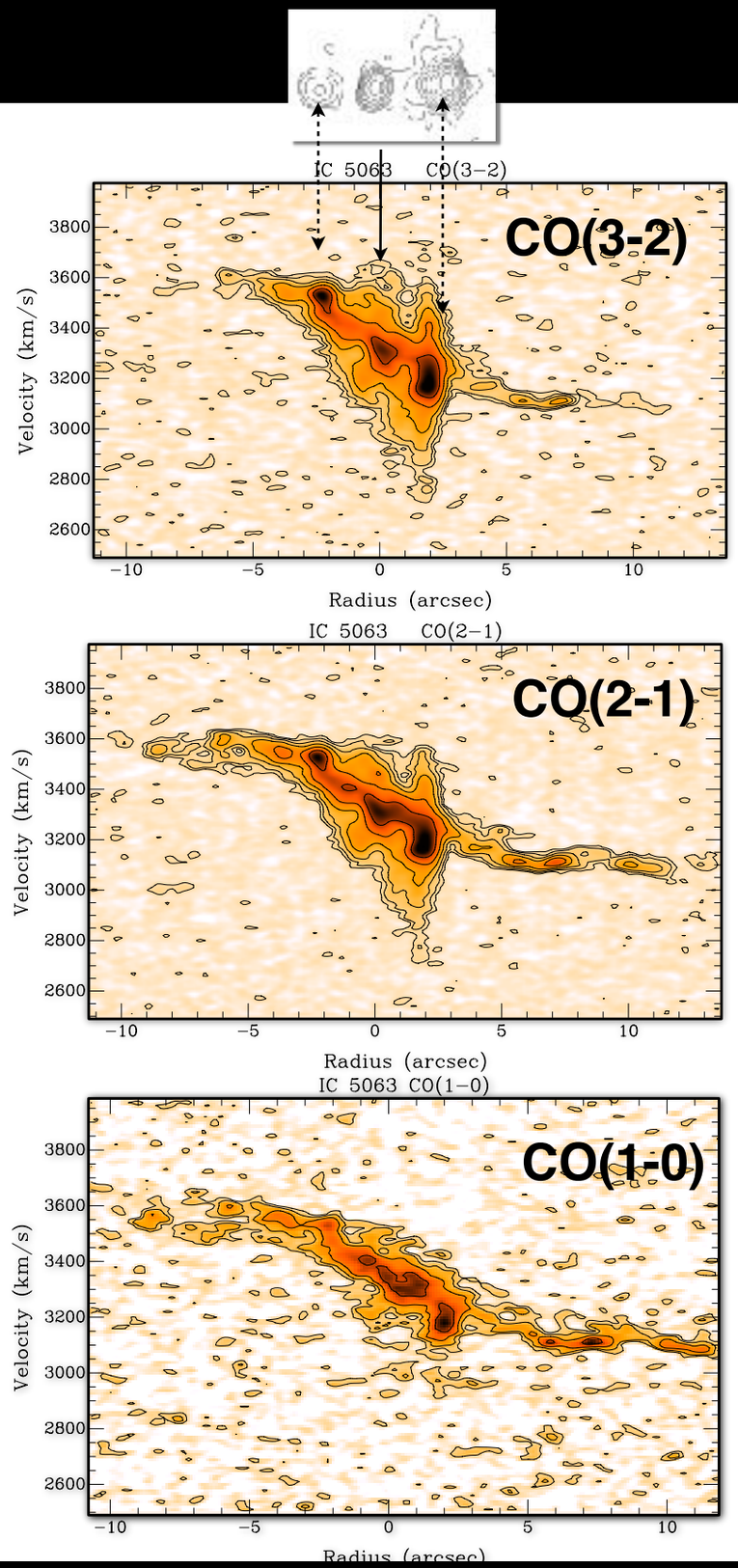
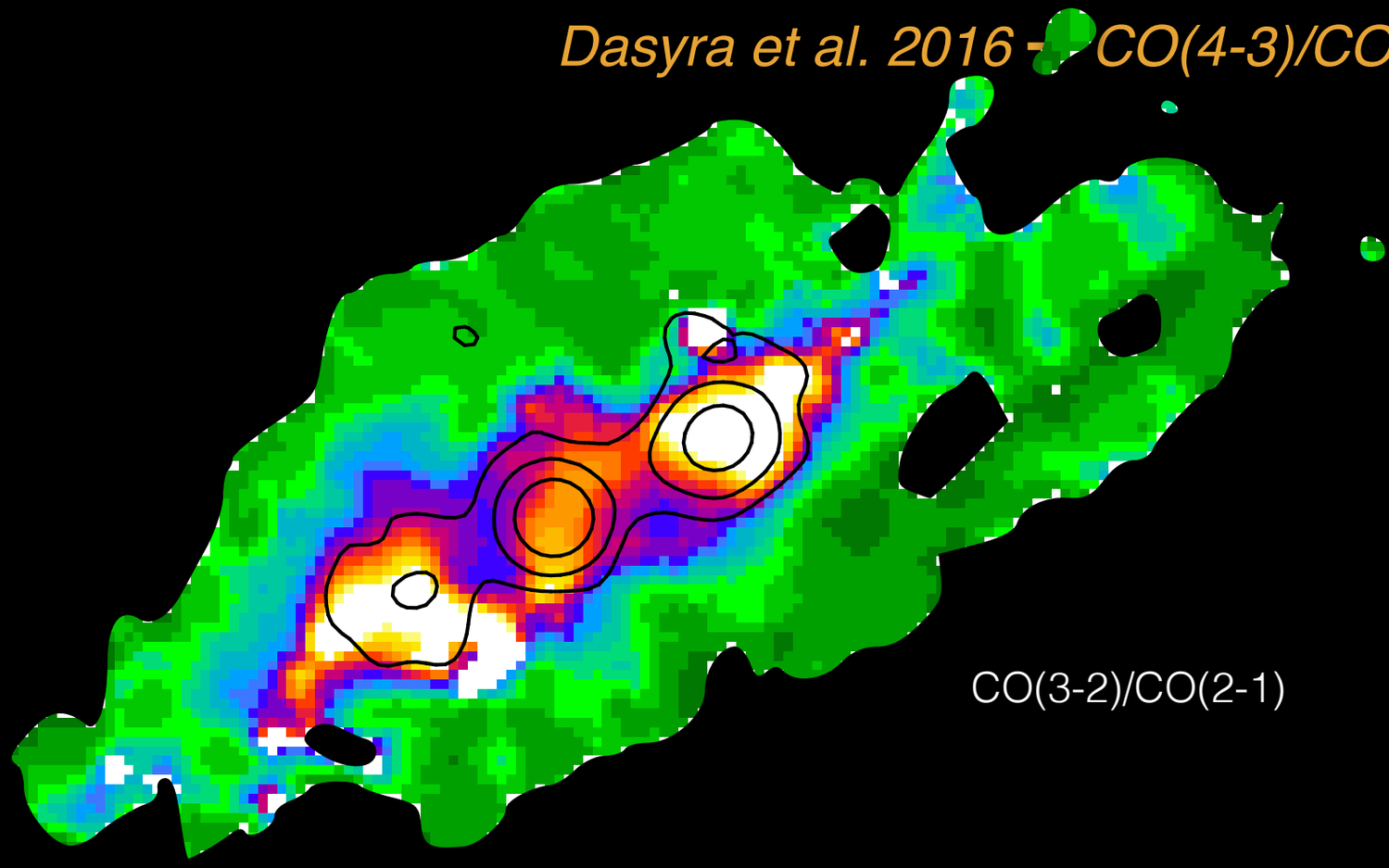
new ALMA results

Oosterloo et al. in prep

Dasyra et al. 2016 - CO(4-3)/CO(2-1)





- Difference in line ratios along the radio jet and in the disk
- Ratio in outer disk like that of spiral galaxies (0.3-0.5)

Clearly different conditions in jet-affected region

- Excitation pattern consistent with outflow driven by cocoon inflated by the jet
- Line ratio in outflowing gas between 1 and 5

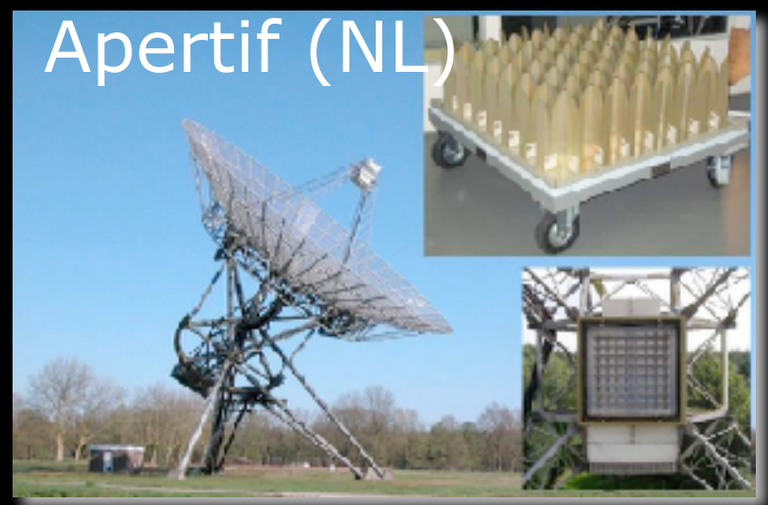
➔ gas must be optically thin

- T_{ex} 30-50 K (optical thin limit; LTE)

- HCO+ detected in the outflow
  => tracing high density clumps

- Outflow mass LOWER than originally estimated ~ few x 10^6 M_{sun}
- Small fraction of the gas will leave the galaxy, main effect of the outflow:

redistribute the gas



HI absorption projects with SKA pathfinders/precursors:

ASKAP: The First Large Absorption Survey in HI
FLASH (PI: E. Sadler)

Apertif-WSRT: Search for HI absorption with APERTIF
SHARP (PI: R. Morganti)

MeerKAT: The MeerKAT Absorption Line Survey
MALS (PI: N. Gupta)

see also *Cool Outflows and HI absorbers with SKA*
by **R. Morganti**, **E. M. Sadler**, **S. J. Curran** & HI SKA Working Group Members

ASKAP - Example of redshift coverage for HI abs

Milky Way HI

$z = 0.192$ HI

$z = 0.885$ OH

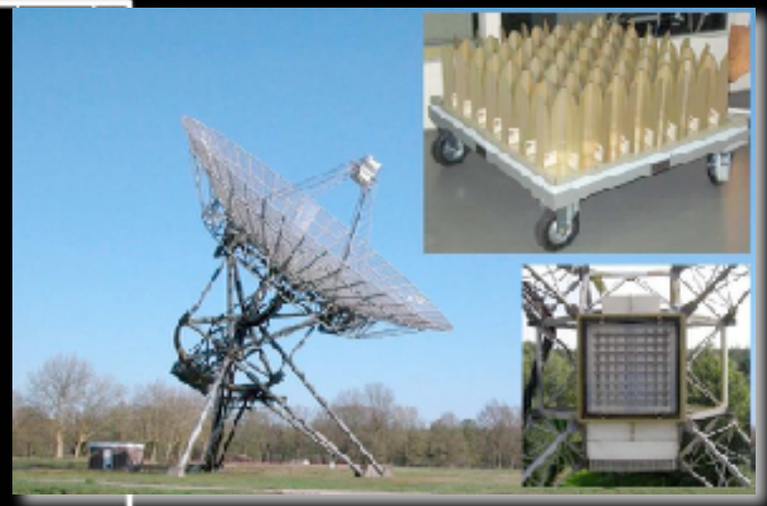
$z = 0.885$ HI

Absorbed Fraction (%)

$\nu_{\rm bary}$ (MHz)

Allison et al. (2016)

Apertif - Phased Array Feed for the WSRT (NL)



PIs: Tom Oosterloo
Marc Verheijen

Declination (J2000)

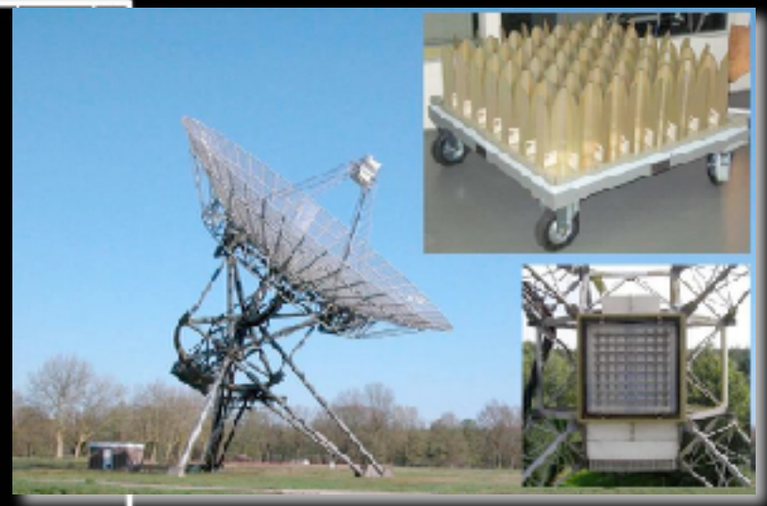
32°
31°
30°
29°
28°

old WSRT

1^h05^m 1^h00^m 0^h55^m 0^h50^m

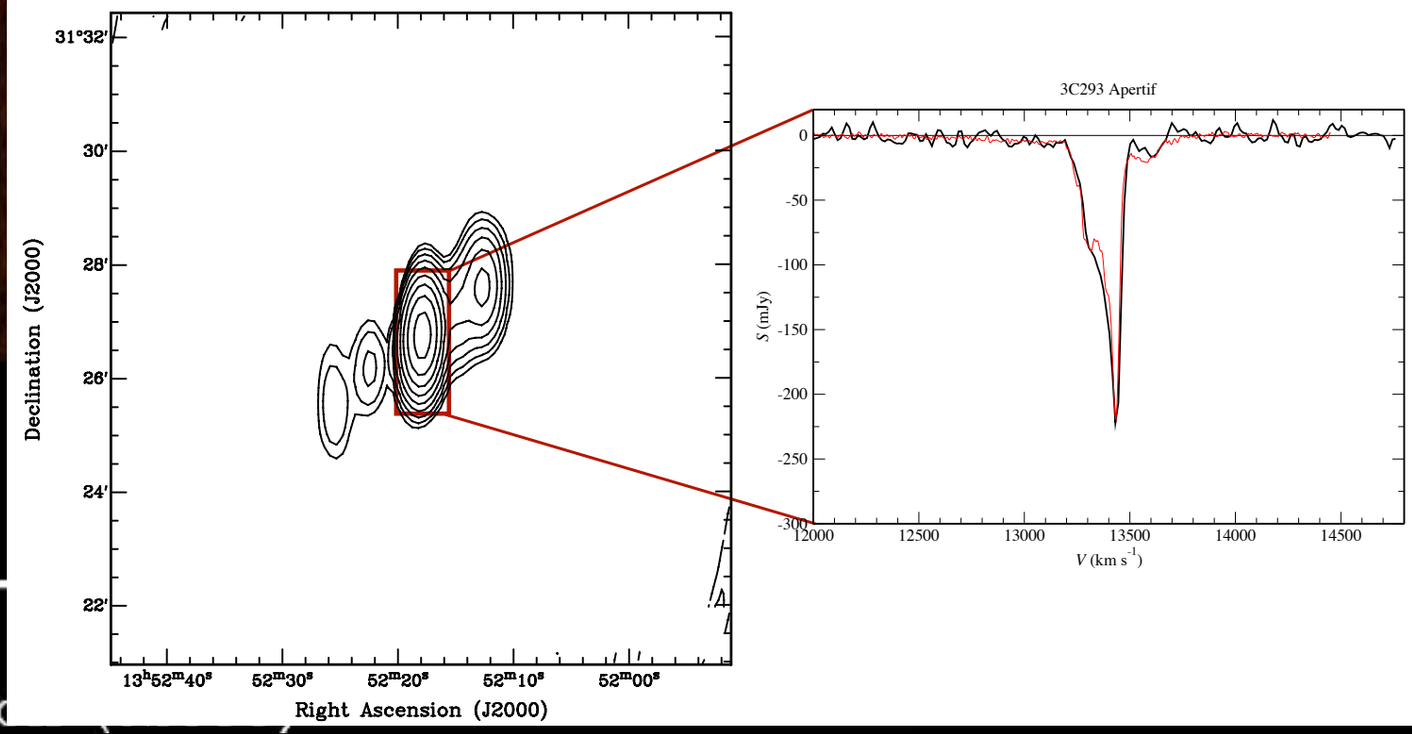
Right Ascension (J2000)

Apertif - Phased Array Feed for the WSRT (NL)



PIs: Tom Oosterloo
Marc Verheijen

Apertif continuum image and HI absorption spectrum of the radio galaxy 3C293



Conclusions

Radio jets can drive HI (and molecular gas) outflows

Mass in the HI outflows from a few x10^6 to 10^7 $M_\odot$, velocities between a few hundred to ~1300 km/s, mass outflow rates ≲30 $M_\odot$/yr

Newly born radio jet particularly efficient in driving outflows: signature of the feedback loop.

Gas efficiently cooling after the interaction: cold molecular final product, warm molecular and HI intermediate (and less massive) phases ➜ BUT mass of the outflows still uncertain!

Only a limited fraction of the gas seems to be able to escape the galaxy: relocating the gas more than expelling it…

HI (observed in absorption) can be used as tracer of cold gas outflows (i.e. link to the molecular phase present)? to be further explored!

Many new HI absorption surveys starting now with SKA pathfinders !